Design Through Digital Making:
A Human-System Collaboration Framework

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Design Through Digital Making:

A Human-System Collaboration Framework

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To my mom, dad, Nick and Matin

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Contents

List of Tables

List of Figures

Summary

In the last 30 years, a large number of experimental architectural projects and whole buildings have been realized using computationally driven fabrication machines and robotics. It is widely claimed that these new technologies are changing the way we think, construct, operate, and design. However, the degree to and areas in which these changes are happening are debatable. This thesis examines recent projects where representational and fabrication technology is integrated into the architectural design and production process. The thesis investigates how new tools and techniques are being adopted, interrogates if their use results in the generation of new design and making paradigms, and identifies potential areas of change and growth.

The thesis provides an overview of existing design and making paradigms, including alternatives to the commonly accepted linear model in which design happens in advance of construction and informs, but does not direct or guide construction. In these alternative models, design and making happen more simultaneously and develop together through collaboration and interaction. Through that discussion, the concept of *emergent design*—design determined through the process of its creation—is unfolded in the context of collaborative design models coupled with digital fabrication tools.

The study accomplished through analysis of forty published projects that claim impactful integration of digital tools – with the explicit goal of creating digital models that drive production. The projects are different in scope, size and program. They are analyzed in terms of their implemented techniques, tools, and system agency and are critiqued to identify patterns and trends in their design and making processes. These elements are instructive for determining the possibility of human-system collaboration within these projects. In order to qualify the degree of that digital autonomy and collaboration in these projects, scales are developed to facilitate the comparison of the projects to discover trends and draw conclusions. At the end of the thesis, several of the most impactful projects are described more deeply as case studies.

Chapter I: Introduction

Background

Architecture incorporates two fundamental parts: 1) design and 2) making. Throughout history, these two processes have been more closely related or diverged from each other depending on location, time, and availability of resources including tools and materials. However, design and making do not happen in isolation, and there is continuous dialogue of influence and information between them (Prall and Dewey 1935; Schon 1992; R. Oxman 2006; Corsini and Moultrie 2018).

Mario Carpo (Carpo and Davidson 2011)—architectural historian—argues that two main models exist in architecture: 1) the model of Brunelleschi, and 2) the model of Alberti. In Brunelleschi's model, architects were responsible for spatial design of architecture and were closely involved in the construction of the building, choosing the materials, construction techniques etc. Alberti's writing changed this role, as he proposed that architecture should be separate from construction and put emphasis on the intellectual training of architects to differentiate them from master builders and craftsmen. The architects still were required to be present on construction site to maintain communication with the other parties involved in the making process, but gradually changed their relationship to builders and to the site (Gourdoukis 2015). There came the need to produce instruction and information documents for better coordination and communication between the makers and the architects. Here, architectural drawings including detailed plans, sections and elevations became a crucial part of architecture. Emergence of drawings also meant that architects did not need to constantly be present on construction site and it furthered the gap between the act of design and the act of building construction (Gourdoukis 2015).

In the 20th century, a growth in "academic, engineering education" further widened the gap between design and making and undermined the impact of making in the design process (Corsini and Moultrie 2018). This describes the division of architectural knowledge between the technical/scientific and theoretical/aesthetic. The technical knowledge became engineering and the theoretical/aesthetic knowledge became what we now consider architecture. This trend also was seen in the Architecture Engineering and Construction (AEC) industry, as building design and construction, contracts, liabilities and responsibilities of the parties involved in the design to construction became more complex.

It is widely claimed that with the rise of new technologies in the past few decades and the influence of other fields in the AEC industry, new workflows, design models and construction methods have evolved which are changing the face of the building industry. Corsini and Moultrie, researchers in University of Cambridge, write that digital fabrication tools like 3D printers, laser cutters, robotic arms and CNC machines and the availability of "maker spaces" have provided an alternative to mass production (Corsini and Moultrie 2018) and made mass customization and 'personal manufacturing' a possibility (Mellis 2014). To understand these shifts and determine their importance, it is necessary to study these technologies to categorize their impacts within and their contexts.

Digital Fabrication

Digital fabrication is defined as computer aided additive, subtractive, or formative methods that manipulate material through automated processes. Digital fabrication processes are broken down into two main groups: 1) computer numerical control (CNC) processes for subtractive fabrication and 2) rapid prototyping (PR) processes for additive procedures (Seely 2004). In describing the potential of emerging technologies in creating a more integrated approach towards architecture, Mitchell writes "by interfacing production machinery with computer graphics systems, a very sophisticated design/production facility can be developed"(Mitchell 1977, 372). Mitchell is describing a system where the two main parts in architectural design—design and making—are coupled and closely work together to influence each other. Gramazio Kohler Research refers to this process as "informing architecture" (Bonwetsch et al. 2016, 489) as coupling the virtual and physical realities allow the linkage of data and procedures (design) to build architecture (make) and vice versa. In other words, the act of physical production of architecture is closely linked to the practice of architecture and this has become possible through constant dialogue and collaboration between involved parties.

Current state of the field

Compared to other industries, architecture has been slow in incorporating new technologies into production (Wilson 2017). Despite contemporary technological advances, architecture still widely relies on the 20th century design-to-production approach and advanced tools are employed primarily to facilitate traditional goals and tasks. A main reason for this is the number of variables at play in AEC projects including budget, schedule, and unpredictable and dynamic conditions of construction sites, which are unreliable and risky compared to plants and factories. In an attempt to reduce the number of variables to create a more controlled condition, complex fabrication typically occurs outside of construction sites in controlled factory environments, especially in those cases where fabrication involves digital tools (Furrer et al. 2011). Although these technologies have not fully found their way to construction sites, there is ongoing research testing their viability at medium and small scales, and over the past few years these technologies have been applied for in-situ construction of large-scale buildings (Dörfler et al. 2019; Block 2019).

Researchers and designers (N. Oxman et al. 2017; Doerfler et al. 2014; Bonwetsch et al. 2016; Angelopoulou 2020) have widely discussed and applied technologies like 3D modeling software, robots, 3D printers, etc. in the creative design process as agents instead of mere passive tools. Technology also redefined collaboration between different human technicians by connecting them from the early stages of design, when previously architects would work through those stages in isolation. This has been transforming the dominant linear design-to-fabrication paradigm used in architecture since the Renaissance (Corsini and Moultrie 2018). Digital fabrication also allowed for embedding material and structural knowledge into digital modeling and used the knowledge for generative design rules (Sharif, Gentry, and Sweet 2016). Some other approaches are not widely practiced in large-scale architectural projects today but designers like Neri Oxman (N. Oxman et al. 2017), and researchers at ETH Zurich (Doerfler et al. 2014; Bonwetsch et al. 2016) have proposed ways to incorporate a process-oriented approach in design through hands-on making. Rapid-prototyping and 3D modeling tools have made these approaches more possible, and the integration of sensors into robotic systems and the utilization of dynamic and open platforms makes a wholly process-oriented approach achievable.

Current Challenges

Although, these changes are promising, this thesis argues that the current state of the field underdelivers relative to its claims. Architecture today is still practiced with an old mindset that interferes with the integration of technology into the design process and, despite technological advancements, our systems and machines are still used to serve traditional design and making models. New systems have the potential to play more influential roles in the field because they could be involved as active participants and exercise higher degrees of agency. However, in most applications this is not achieved and the designers are still in charge of the whole process. Also, due to the complexity of working with these technologies, design still is removed from making and collaborative and process-oriented practices are rare in industry.

An important barrier is defining and establishing new ways of interaction and dialogue between human and technology so advanced machines and tools can be effectively integrated into the architectural process. The work to address this issue has taken many different directions, from defining new theoretical collaborative frameworks (Corsini and Moultrie 2018; R. Oxman 2006) to development and adaptation of technologies specific to architectural problems (Bonwetsch et al. 2016), to development of intelligent agent tools (Doerfler et al. 2014; Bidgoli, Kang, and Llach 2019; N. Oxman et al. 2017). However, we have not developed measures and definitions to examine these efforts, so we remain unable to compare them in order to find trends or understand their effectiveness.

This thesis proposes a new framework to think about the integration of technology into the architectural process through human-machine/human-system collaboration in order to redefine our thinking about design and making so that they can be seen as one cohesive act.

Chapter 2, includes a literature review to give an overview on existing design and making frameworks that emphasize the importance of making while designing and ways to narrow the distance between the two acts. Also, the same chapter discusses and proposes possibilities within the field of digital design and fabrication. Chapter 3 describes a methodological approach to study and examine case study projects in order to identify common features and trends between them. To identify those trends, a point-based system is developed which defines relevant project elements and rates their effectiveness in a human-system collaboration scale. Chapter 4, analyzes and presents the results of applying the described method to forty case studies. Chapter 5, closely discusses five case studies selected from the poll of forty mentioned case studies in order to analyze and describe the current state of the field and potential opportunities with it. Chapter 6 is a conclusion of findings and discussion of future works.

Chapter II: Shifts in design paradigms in the digital age

The invention of digital fabrication introduced new possibilities to our design and fabrication approach. However, there are debates about the area and degree of this change, and whether the digital tools are facilitating or limiting the design/fabrication process (Corsini and Moultrie 2018). The emergence of new tools makes design approaches and forms that were not previously possible now feasible, but the high level of accuracy these tools provide and the technical precision need to use them limit a designer's ability to maintain contact with material and with the making process (Corsini and Moultrie 2018). Also, these advanced tools are still used for traditional goals, as they are used to improve productivity and reduce production time instead of being fully integrated in the process or utilized transformatively according to their capacity. This chapter presents and analyzes some of the existing conceptual paradigms in design and making and how new technology is affecting the creative process.

In the 20th century, influential designers like Le Corbusier advocated for continuing the practice of the one-dimensional design-to-construction model passed down from the Renaissance. Le Corbusier emphasized a goal-oriented approach in architecture where design is completed prior to construction and informs it: "Man walks in a straight line because he has a goal and knows where he is going; he has made up his mind to reach some particular place and he goes straight to it" (Le Corbusier 1947, 11).

Beth Preston, professor of philosophy and technology, explores, defines, and critiques this design approach, which she calls the "central control model". Preston describes it as a "directive and determining force" and lists four criteria for it (Preston 2013):

1- The mental phase of design is distinguished from the act of construction and happens prior to it;
2- Designing is done by an individual;
3- Construction happens through step by step following of the design instructions;

4- There is no intelligence associated with construction;

In the central control model, the designer absorbs all the desired inputs and produces construction illustrations—drawings, for example—which act as instructions for making. Preston goes on to critique the central control model for failing to address 1) collaboration between multiple designers and 2) coincidental events. Preston explains that design and construction is a collaborative process in which a group of people is involved, not necessarily an individual. She further elaborates that the central control model encourages repetitiveness and limits creativity in the production of novel work (Preston 2013).

Although the central control model is still the widely accepted concept of the design process, alternative approaches have long existed. As early as 1934, John Dewey, a renowned American philosopher, theorized a more integrated approach towards design and argued that, in most cases, design and making happen in closer contact with each other or even simultaneously. Dewey writes that it is rare to find cases where ideas and objects cannot affect each other (Prall and Dewey 1935). In his framework, tangible touch and contact between designer and material impacts the way the material is used and how the design is formed. Dewey's opinion is closer to the design paradigm prior to the Renaissance, when building and design were happening simultaneously. To describe the design and construction process of medieval cathedrals, Dewey states "plans grew as the building grew" (Dewey 2005, 54). This integrated process contradicts the central model and describes construction and design as evolving together to simultaneously inform and influence another. A key component here is the designer, who is responsible for bridging between design and construction.

Donald Schon also place central emphasis on the figure of the designer, but requires the designer to make tangible contact with materials and methods (Schon 1992). In this model, design is formed through the interaction of the designer with material, tools, context etc. Design continues through continuous interaction between the designer and a 'visual medium'(Schon 1992, 5). Schon embeds knowledge *about* design into the design process.

This knowledge cannot solely be communicated through words, so it is usually represented through the experience of making. In this process, “sensory and bodily knowing” are at play: The designer first ‘sees’, then creates and then sees the work again to reflect and continues further designing(Schon 1992, 5). This creates a back and forth dialogue between the designer and a visual medium, like drawings or models, through which the designer learns and discovers new possibilities.

Reading Preston, Dewey, and Schon together, one can see a framework for theorizing a collaborative/interactive approach to design. In this paradigm, design does not happen in vacuum, nor fully before the act of making starts. Instead, the design is developed by embedding knowledge of material, machinery, and context throughout the process. With technological development and the rise in the popularity of digital fabrication, more emphasis has been focused on interaction and the type of relationship: between the users/designers with other designers, tools, materials and machines. Researchers and designers have utilized this collaborative/interactive approach to collaborate with other human designers, passive tools, and, most recently, agent-tools and non-human agents (N. Oxman et al. 2017).

In her paper on extending human cognition through robotic fabricators, Shani Sharif extends this framework through the integration of digital fabrication tools into the process. She proposes that interaction opportunities between the designer, environmental context, materials and machines will reduce the disconnect between the designer and the act of making (Sharif 2019). Sharif discusses the possibility of creating closed interactive loops in which design and fabrication happen simultaneously. To create a closed-loop the machine should be equipped with sensors to take input from the user and environment and provide feedback in real-time. However, this method does not necessarily consider a high level of agency for the machines as it is focused on human cognition, which is developed through working with tools and machines (Sharif 2019; Schon 1992). The user’s close contact and involvement with the production process removes the need for equipment sensors, as cognitive activities surpass conscious thoughts to include the environmental and design context. In this model, the integrated tools and machines are utilized as extensions of the designer’s body and the user discovers new design and fabrication possibilities as she carries on the making process.

Technological advancements exclusively do not create a difference in the process, since in many cases the focus is mainly on automation of construction/fabrication. Also, technology imposes specific limitations in the process which might limit and control user’s involvement in the making process and therefore, widen the gap between design and making (Sharif, Gentry, and Sweet 2016). However, researchers have invested a great deal of effort in developing the type of technology that allows for integration of robots in the process by equipping them with sensing systems in order to create seamless and adaptive fabrication processes (Doerfler et al. 2014). Also, there have been several experimental projects on human-machine interaction in design and making where digital tools were influential in realization and construction of the work (Furrer et al. 2011; Knippers, Jan et al. 2012; Doerfler et al. 2014). The research pavilions built by institutions like ETH Zurich, University of Stuttgart and Tongji University are among these works. In these projects, a great deal of effort has gone into adapting and developing tools specific to architectural contexts. Similarly, other researchers like the MIT Media Lab have successfully involved non-human agents into the architectural process (N. Oxman et al. 2017).

Some other collaborative/interactive models focus on machine/system intelligence and their degree of agency. Researchers at Carnegie Mellon University (Bidgoli, Kang, and Llach 2019), have discussed the production of art as an interactive process between humans and agent systems. Their work is not as focused on human interactions with machines and systems, but rather emphasizes technological advancements like Artificial Intelligence (AI) that enable the integration of digital tools in the creative process (Bidgoli, Kang, and Llach 2019). They argue that, despite the development of new tools, there has not been a significant shift in design and production models because the system agents at play are still heavily influenced by their creators and the data and information fed to them. In this scenario, the systems cannot provide input into the design process equal to the human agent. However, the designer is no longer the center of design and making because their influence is one step removed from the generation of the final products: the relationship between the designer and the final design becomes indirect as the system acts as an intermediary agent.

These researchers discuss the interaction between humans and their tools, and this relationship's impact on design and making. Based on these studies, there are three models for understanding collaborative/interactive design and making:

1- Direct interaction between human and unintelligent tools/machines.
2- Direct interaction between human and intelligent tools/machines.
3- Indirect interaction by human through intelligent tools.

What they show is that design and making are *not* separate processes; rather, design is a process of learning and discovery that occurs through a designer's experimentation with tools and materials. The results of the process, then, should not be pre-determined by the unbending will of the designer, but require uncertainty to be fully achieved. Different researchers use different terms to describe this phenomenon: e.g. spontaneity, improvisation, or emergence (Corsini and Moultrie 2018). The discussed researchers have also extended these thoughts into digital tools and fabrication. Although some may believe that the separation and functional rigidity imposed by digital tools limit the designers' effectiveness in a collaborative/interactive design process, the cited researchers state that digital tools actually expand the ways in which a designer can engage with a collaborative/interactive process.

<u>Emergence in Design</u>

In a collaborative/interactive design model, many variables are involved. As discussed in the previous section, design does not happen in a pre-determined manner but rather finds many possible shapes in response to a variety of situated factors (Holzer, 2008; Harrison et al., 2015). This interactive/collaborative system enabled by digital fabrication tools can revive some of the inherent characteristics of pre-renaissance design models like spontaneity and uncertainty (Corsini and Moultrie 2018).

Tim Ingold— the chair of Social Anthropology at the University of Aberdeen— questions the deterministic view that architecture has an ideal finished state and argues that through construction and occupation, architecture is in continual process (Doherty 2009). Referencing David Turnbull and John James, Ingold compares the construction site of a cathedral to a modern research laboratory where multiple groups, make their own progress towards a shared goal (Ingold 2013). In this set up, different crews worked on different sections of the building, so it was not possible to determine the final outcome and the building took form as different pieces were completed next to another. Ingold uses the cathedral of Chartres as an example to explain this process. The building, was rebuilt following a fire between years of 1194 to 1230. During the construction course, teams of laborers worked under at least nine master masons, in multiple short efforts in more than thirty years. Ingold argues that under this condition, the final state of the cathedral could not be predicted or exactly planned. The nature of the work, necessitated a responsiveness to situations that naturally arose out of the process.

This discovery and spontaneity has been viewed as 'emergent design' (Corsini and Moultrie 2018). Emergence and ambiguity has been discussed in a variety of context and disciplines; as a natural process of design process (Prall and Dewey 1935), or as unexpected glitch and noise (Marenko 2015). The concept of emergence is also discussed in Dewey's writings. Dewey describes emergence as an organic and unexpected event that is a result of the production of work that " is not a learned document or an illustration of something familiar" (Dewey 2005, 78). Emergence is sudden and "belongs to appearance of material above the threshold of conscious"(Dewey 2008, 82). In Dewey's opinion, emergence is a product of a long period of activity, experience and experiment.

Emergent design has also been discussed in context of computational modeling and shape grammars (Knight and Stiny 2001). Unlike Dewey, who sees emergence as the natural result of activity and experiment, Knight believes that emergence can happen through 'unambiguous-ambiguity' and can be found "anywhere you have a rule to find it" (Knight and Stiny 2001, 369). This opens the possibility for a designer to plan for emergent situations and design the rules to achieve it.

The concept of emergence in design has been acknowledged and widely discussed. However, this brings in the question of how this concept can be used in design process and especially in response to digital tools (Corsini and Moultrie 2018). Many scholars (Preston 2013; Corsini and Moultrie 2018) have analyzed the current state of digital fabrication and have proposed ways to incorporate concepts of emergence and spontaneity in digital fabrication, and similarly, experimental findings (Furrer et al. 2011; Doerfler et al. 2014; Dierichs and Menges 2016) show that digital fabrication tools can produce emergent outcomes.

The central control model does not account for the necessity of emergence because it assumes that design happens in isolation and not through encounters with other factors. Preston (Preston 2013) proposes three alternatives to disrupt the central control model. Her approach provides designers with alternative descriptive strategies like ‘habits and practices’ instead of prescriptive resources like plans and drawings (Preston 2013). The three approaches are:

1- Appropriate and extend;
2- Proliferate and select;
3- Turn-taking

Corsini and Moultrie (Corsini and Moultrie 2018), build on Preston’s alternative models to identify ways to involve digital fabrication tools in the creative process. They explain that in Preston’s model the “appropriate and extend” approach focuses on the potential of building on existing models and ideas where the existing structure can be used as an inspirational tool to produce new design and forms. Through interaction with an existing object, new ideas are formed. The “proliferate and select” approach is an interactive process in which trying and studying multiple iterations and selecting and testing suitable options, new designs and ideas are formed. The third approach, “turn-taking”, is focused on interaction between individuals and communities where collaboration and exchange of ideas result in the generation of new results.

Corsini and Moultrie argue that digital fabrication tools can potentially generate variability, so they add a fourth strategy to Preston's framework, that of 'exploiting spontaneity'. The additional strategy uses 'glitch', or happy accidents, that occur during the design process as an opportunity for inspiration and new ideas (Corsini and Moultrie 2018) . In conclusion, Corsini and Moultrie propose that using 1) partial readymade objects, 2) imitation of existing products and designs 3) collaboration with other designers and 4) making with interactive digital fabrication tools open opportunities for creative outputs. Although Corsini and Moultrie propose these models in the context of digital fabrication, it can be argued that the first three techniques are not specific to digital fabrication and can be used in design processes regardless of the types of tools used. However, the fourth introduced model has been discussed mostly in the context of emerging digital techniques including interactive and intelligent digital fabrication.

Based on this review, emergence through digital design and fabrication can be achieved through multiple means. Like in the example of emergence in shape grammars, 'making' might not be involved and the focus may be solely on design. Emergence can be planned or be unexpected in the form of a happy accident. Similarly, emergence is possible in a process-oriented/bottom up approach where agent-based systems and rules are organized in order to promote emergent results. At the same time, it can be argued that some of the discussed design-making frameworks in the previous section are applicable to achieve emergence. In summary, emergence in digital fabrication is accessible in the following forms:

1- Happy accidents during making/fabrication.
2- Through an interactive/collaborative process between users and unintelligent systems.
3- Through an interactive/collaborative process between users and agent intelligent systems.

As architecture continues to rely ever-more on mechanical systems, the topic of emergence in digital systems is particularly relevant. Through automation and other systems, humans are removing themselves from production systems, and are being removed. It is important at this moment to understand how we can work with our new tools for the best results.

Chapter III: Redefining Digital Fabrication

This chapter presents the methodological approach undertaken to perform a study on the integration and adaption of digital fabrication tools into the architectural process. The chapter identifies contemporary projects that incorporate digital tools to find trends between them and defines elements that distinguish them. The chapter proposes a system to evaluate the success of these projects in areas of human/machine collaboration, design emergence and narrowing the gap between design and making.

The study is performed in four parts:

1- Project selection
2- Project feature analysis
3- Human-system collaboration scale
4- Identification of trends

Part 1- Project Selection

The goal of project selection was to study projects that had digital fabrication as a fundamental component of the project. The research intent was to analyze noteworthy and groundbreaking digital fabrication projects to see how successfully digital fabrication tools were integrated into the overall process.

The projects were selected through a survey of online architecture publications that include or put emphasis on digital fabrication. The surveyed publications include Archinect.com, ArchDaily.com, Parametric Architecture magazine, Dezeen.com. Some medium and lab-scale projects were discovered through survey of academic journals and online research resources.

After collecting a wide breadth of digital fabrication projects, I curated a selection for review in this study. The curation criteria were emphasis on fabrication, preference for new or groundbreaking-for-their-time techniques, and avoidance of repetition. My final selection included forty (40) projects, which vary depending on their scale, program, structural capacity, building systems etc. To address this diversity, I divided the project equally into two categories of 1) large-scale and 2) medium-scale. Projects that include enclosure, have structural capacities, or/and are designed to house occupants are under the large-scale category. Projects like pavilions in which the structure is supporting itself but does not include building systems are considered the small-scale.

The Bubble

The Bubble was Franken Architekten's design for BMW's trade presentation at the 1999 International Motor Show (IAA) in Frankfurt. The Bubble is a self-supporting structure, and its form resembles a drop of water. The structure consists of 305 curved acrylic glass plates installed on CNC milled aluminum ribs. The acrylic glass plates were heat formed on CNC fabricated foam blocks and transported to the site for assembly (Franken 2010; Archello 2020).

Figure 1: The Bubble by Franken Architekten (Busam 1999).

The Rebuilding of Teatro Petruzzelli's Inner Dome

The reconstruction of Teatro Petruzzelli in Bari, Italy was completed in 2008. The new dome was designed by the Superintendent from the National Environment and Architectural Heritage Body in Italy. The structure of the dome is made of glued laminated timber, which allowed the designers to use pieces thinner in width compared to the original timber structure. For this project the company Stratex S.p.A. was commissioned to provide all the wooden structural work. For pre-fabrication of the structural pieces, Startex developed a digital structural model based on the designers' model. The structural model was used for CNC fabrication of the structural components which were then brought and assembled in construction sites (Tegola 2014).

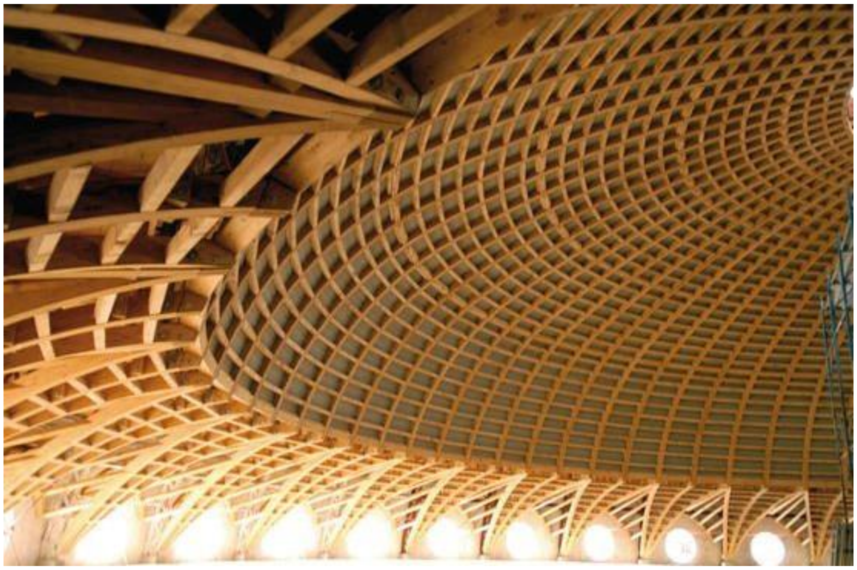

Figure 2: Teatro Petruzzelli's Inner Dome (Tegola 2014).

290 Mulberry

290 Mullberry street (2009) is a 13-storey residential building in New York designed by SHoP Architects. The building is distinctive due to its undulating brick façade. BIM played an essential role in this project and made collaboration between different teams from early stages of the project possible. The brick facade panels were pre-fabricated and transported to the construction site. SHoP Architects used physical prototyping in design of the facade. Based on the architect's digital model, the contractor developed their own model for CNC milling and prefabrication of the façade panels (Anderson 2010; Sharples 2009).

Figure 3: 290 Mulberry by SHoP Architects (ArchDaily 2008).

O-14 Tower

In 2010, Reiser + Umemoto completed the O-14 Tower—a 22-storey commercial building—in Dubai. The design incorporates a perforated concrete shell that is structural and removes some of the load from the tower's core by bracing the building against lateral loads. In construction of the shell, CNC cut polystyrene foam blocks were inserted into the reinforcement matrix to act as the negative form for the cast in place concrete (Reiser + Umemoto 2012; Reiser, Umemoto, and Ocampo 2010).

Figure 4: O-14 Tower by Reiser + Umemoto (Garrido 2012).

Gatehouse

The Gatehouse (2010) is a part of the master plan by Barkow Leibinger Architects for Trumpf factory—a machine/tool company-- campus near Stuttgart, Germany. The Gatehouse is the reception building. The structure and form of the design exploit the possibilities of digital fabrication and represent Trumpf company's profile as a tool and manufacturing company. The building features a twenty-meter cantilever steel roof at its entrance. Laser cut and welded sheets of metal are seen through the building (Tegola 2014; Architect Magazine 2012).

Figure 5: The Gatehouse by Barkow Leibinger Architects (Franck 2011.

Spencer Dock Bridge

Spencer Dock Bridge is located in Dublin, Ireland and was designed by Amanda Levete Architects. The bridge has a soft fluid geometry and incorporates a combination of precast and in situ reinforced concrete construction. The formwork is made of high density expanded polystyrene foam coated with resin to achieve a smooth finish. The formwork is CNC cut directly from the architects' digital 3D model (Minner 2011).

Figure 6: The Spencer Dock Bridge by Amanda Levete Architects (Fuehrer 2010)

Art Gallery of Alberta

The Art Gallery of Alberta in Edmonton, Canada was an expansion on an existing concrete building designed by the architect Don Bittoft in 1969. Randall Stout Architects, Inc. won the competition for the project in 2005. The architect's design included a two-story vertical addition to the existing building and an additional atrium. The design features a band of stainless-steel running around the interior and the exterior of the building which was fabricated by Zahner. In fabrication of the stainless-steel ribbon, Zahner worked closely with the designers by providing them with mock-ups to assist with design realization and development. The support structure steel was detailed and fabricated by Empire Iron Works, for which they created a BIM model based on the designers' Rhino model. A CNC bending machine was used for bending the steel pipes for the support structure (Tegola 2014; Zahner 2020; Empire Iron Works 2020).

Figure 7: The Art Gallery of Alberta by Randall Stout Architects (Randall Stout Architects 2020).

Perot Museum of Nature and Science

Perot Museum of Nature and Science (2012) is located in Dallas and was designed around the concepts of nature, sustainability and technology. Morphosis designed the museum with the goal of making the building itself a tool for science education and to evoke curiosity about nature in the visitors. The building is in form of a large cubic mass floating over the site's landscape. Inspired by nature, the façade is designed to resemble layers of sedimentary rock. CNC milling was used for digital fabrication of the formwork for the pre-cast panels used in the atrium and the façade. BIM was crucial in coordination and management of the project (Morphosis 2012; Garber 2014).

Figure 8: Perot Museum of Nature and Science by Morphosis (Baan 2012).

Landesgartenschau Exhibition Hall

Landesgartenschau Exhibition Hall (2014) is the first structure to be entirely fabricated with robotically fabricated lightweight timber construction. The structure was designed and constructed by University of Stuttgart as a research project/prototype building to demonstrate the capacities of digital fabrication and computational modeling at the time. Landesgartenschau Exhibition Hall consists of two dome-shaped areas made with convex polygon plates. The form and geometry of the individual plates are realized through generative parametric modeling. The plates are pre-fabricated with a CNC machine and a robotic industrial arm but were manually assembled on the construction site (University of Stuttgart 2014; Winston 2014; Menges et al. 2019).

Figure 9: Landesgartenschau Exhibition Hall (Nebelsick and Halbe 2014).

Petersen Museum

The renovation of the Petersen Automotive Museum (2014) was a collaboration between Kohn Pedersen Fox (KPF) and Zahner Company. KPF's design for the building includes an aluminum façade with curved steel ribbons that was fabricated in Zahner's fabrication shops. Zahner provided KPF with mock-up models which helped the designers to make informed decisions based on the fabrication and material capacities. For fabrication, Zahner used several of its patented technologies. BIM was important in collaboration and communication between the involved parties (Zahner 2014; Coleman and Cole 2017).

Figure 10:Petersen Museum by KPF and Zahner Company (Zahner 2014).

The Global Center for Health Innovation building

LMN completed the Global Center for Health Innovation building in Cleveland, USA in 2014. LMN had an integrated approach towards the design and construction of the building. Rapid prototyping and parametric modeling were fundamental in the design of the building and especially the façade while, BIM and digital fabrication were important in the construction process. The façade is covered with pre-cast concrete panels that are created with CNC milled formworks (LMN 2020).

Figure 11: The Global Center for Health Innovation building by LMN (LMN 2020).

Shanghai Arts Center

Archi-Union Architects, combined robotic fabrication with traditional materials in design and construction of the Shanghai Arts Center in 2016. On site robotic fabrication was used for the construction of the adulating brick façade of the building. Grey bricks salvaged from the original building were used to construct the front elevation of the building. Archi-Union maintained the original building's front exterior wall and used it as the base for the new façade. A mobile robotic arm was used for in situ construction of the façade. Conventional construction methods are used in other areas of the building (Griffiths 2016; Archi-Union 2016).

Figure 12: Shanghai Art Center by Archi-Union (Lin 2016).

Triple S

Triple S is inspired by Thai traditional weaving handicraft. The building is designed by Chanita Chuaysiri and constructed by Siam Research and Innovation Company (SRI). The name Triple "S" refers to the main concepts consisting of Surface, Shelter and Structure. The walls of the building are 3D printed in form of multiple concrete blocks in lab environment and then assembled on site. The building incorporates a conventional roof, doors and windows(Lapyote Prasittisopin 2017; AD Editorial Team 2018) .

Figure 13: Triple S by SRI (Chanita Chuaysiri 2017).

MX3D Bridge

MX3D bridge (2018) is entirely 3D printed out of stainless steel to cross over the famous Oudezijds Achterburgwal canal in Amsterdam. Joris Laarman Lab designed the bridge, and the fabrication is a collaboration between multiple large teams including MX3D, Arup, ArcelorMittal and multiple other parties to provide robotics and digital fabrication expertise including Autodesk and ABB. A robotic industrial arm is used for 3D printing the bridge in MX3D's lab (Arup 2018; MX3D 2018).

Figure 14: MX3D Bridge (MX3D 2018).

St Mary Chapel

St Mary Chapel is an extension to St Mary Mercy hospital in Livonia, Michigan. The project includes a roman catholic chapel, a Muslim prayer room and a reflection room. The building is designed by PLY+ and was completed in 2018. The building is distinguished by its conical façade corner with woven brick pattern. Robotic carving was used in the fabrication of three primary liturgical element of tabernacle, altar, and ambo (done by the Quarra Stone Company).

Figure 15:St Mary Chapel by PLY+ (Smith 2018).

Venue B Conference Hall

Venue B Conference Hall was designed and constructed for the 2018 World Artificial Intelligence Conference (WAIC) in Shanghai, China. Archi-Union Architects designed the building with the concepts of technology and human-machine collaboration. The project incorporates a fully pre-fabricated structure which allowed the project to be completed in about one hundred days. Robotic timber construction was used in the pre-fabrication of structural pieces, and 3D printing techniques were used in the fabrication of the Coffee Pavilion located at the bigger of the two garden courtyards and some of the indoor furniture used in the building (Shuang 2018; Lekka Aangelopoulou 2018).

Figure 16:Venue B Conference Hall by Archi-Union (Tian 2018).

Inkstone House OCT Linpan Cultural Center

Archi-Union Architects completed the Inkstone House OCT Linpan Cultural Center in 2018 in Chengdu, China. Chinese culture, specifically calligraphy, was the main design concept informing this project, and parametric modeling and robotic fabrication were fundamental to the design and construction of this two-story building. While Archi-Union was in charge of the design of the building, Fab-Union—Archi-Union's sister company—completed the pre-fabrication of the building components (Shuang 2019; Schuler 2019).

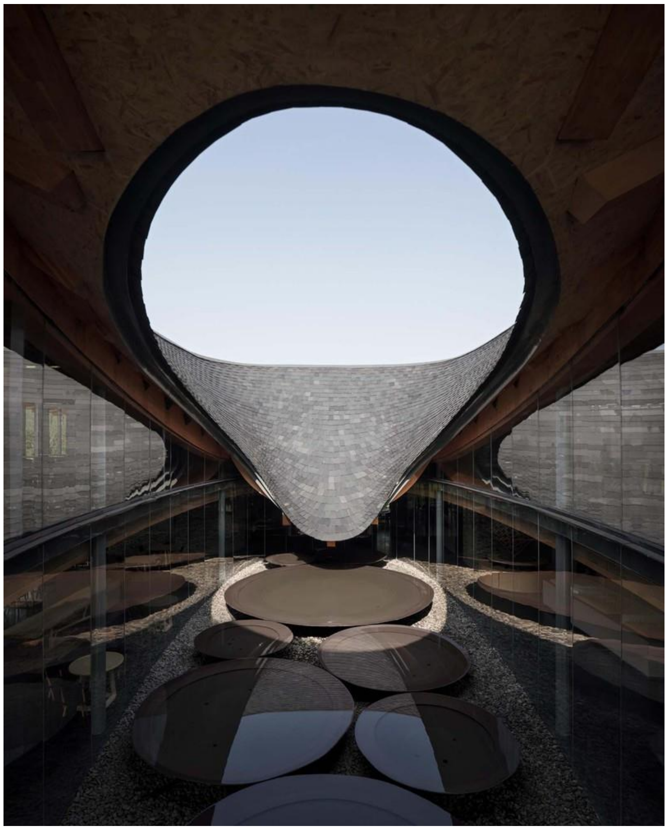

Figure 17:Inkstone House OCT Linpan Cultural Center by Archi-Union (Su 2019).

DFAB House

The DFAB House (2018) is constructed under the direction of the National Center of Competence in Research (NCCR) Digital Fabrication, a Swiss National Science Foundation research program. The project is a collaboration between ETH Zurich and industrial partners and is a hybrid of in-situ and pre-fabrication methods. In the DFAB House, the focus is on the automation of architectural construction through the development of custom digital fabrication tools and unique design and fabrication techniques specific to architectural problems. Technologies including the In situ Fabricator, Mesh Mold, Smart Dynamic Casting, Smart Slab, and robotic Spatial Timber Assembly are utilized (DFAB House 2020).

Figure 18: The DFAB House (Keller 2019).

Dubai Municipality Building

In situ robotic 3D fabrication is key to the construction of Dubai's Municipality Building (2019). The building is completed by Apis Core—a US based company specialized in 3D printing—and is one of the largest 3D printed buildings in the world at the time of this thesis's publication. Digital fabrication significantly reduced the need for labor on the construction site and only three workers and a 3D printer were required for construction (Mary Meisenzahl 2019; Block 2019).

Figure 19: Dubai Municipality Building by Apis Cor (3D Printing 2019).

Delas Frères Winery

Delas Frères Winery (2019) located in Rhone Valley, France, was designed by Carl Fredrik Svenstedt Architect and is distinguished by its unique undulating stone façade. Robotic carving was used in prefabrication of the façade. Individual façade units were pre-fabricated in shop environment in a human-robot collaborative process. Manual labor was used in the installation of the façade in the construction site (Paola Pintos 2020; Minutillo 2020; Block 2020) .

Figure 20: Delas Frères Winery (Glasser 2019).

Fish Sculpture

Frank Gehry Partners designed the figurative Fish Sculpture in 1992 for the Olympic Village in Barcelona. The form was designed through a combination of physical modeling and digital modeling with a CAD-CAM software called ‘Computer Aided Three-Dimensional Interactive Application’ (CATIA). In collaboration with other industrial partners, including the aerospace industry, Frank Gehry Partners simulated the manufacturing the process using CATIA (Tegola 2014).

Figure 21: Fish Sculpture by Frank Gehry Partners (Danilin 2018).

D-Tower

D-Tower (2001-2003) is a media project designed by Studio Knox and is located in Doetinchem, Netherlands. The pre-fabricated tower is twelve meters high and interacts with the city through changing lights. The lights change color according to the data from the D-Tower website, where the city residents can respond to a questionnaire on their emotions and feelings. Polyester is the main material in the tower surfaces, which was formed through a CNC generated molding technique (arcspace 2012; Thomsen 2007; V2 2020).

Figure 22: D-Tower by Studio Knox (D-Toren 2020).

ArboSkin Pavilion

ArboSkin Pavilion (2003) was made with 90% renewable materials based on the concepts of sustainability and digital fabrication. The freeform pavilion was designed and fabricated by ITKE at University of Stuttgart in Germany as a demonstration of the structural properties of the bioplastic material (plastics made from renewable biomass resources) for applications in the AEC industry. The components used in the structure were pre-fabricated and transported to the construction site. CNC milling was the primary digital fabrication technique (Griffiths 2013).

Figure 23: ArboSkin Pavilion by ITKE in University of Stuttgart (Halbe 2013).

Winery Gantenbein

This project was an extension on a vineyard in Fläsch, Switzerland in 2006. Gramazio Kohler Architects designed and fabricated the brick facades. The brick patterned façade allows for light penetration to some of the interior areas and was fabricated using an industrial robotic arm. In fabrication, Gramazio Kohler Architects used the robotic methods that they had already developed at the ETH Zurich (Bearth & Deplazes Architekten and Gramazio Kohler Architecture 2006).

Figure 24: Winery Gantenbein by Gramazio Kohler Architects (Feiner 2006).

Radiolaria Pavilion

Radiolaria Pavilion was fabricated using the world's largest 3D printer at its time in a collaboration between Shiro Studio and D-Shape in 2009. The monolithic pavilion has a free-form complex structure and is made of an artificial sandstone material. This structure was constructed as a mock up for a larger pavilion which was planned to be fabricated in 2010 (Andrea Morgante 2017; Turner 2009).

Figure 25: Radiolaria Pavilion by Shiro Studio (Dezeen 2009).

One Main

One Main was completed in 2009 by dECOi Architects for the penthouse office of an investment group in green building and clean energy technologies (CChange). The design includes fluid forms throughout the space including in the floor, ceiling and furniture. All elements were CNC milled from forested spruce plywood. Automated algorithms were used to generate milling files from the design parametric digital model. The fabrication process was seamless and the components were directly CNC cut from the designers' digital model (dECOi architects 2016).

Figure 26: One Main by dECOi Architects (Grassl 2009).

ICD/ITKE Research Pavilion 2012

The research Pavilion (2012) by ICD/ITKE at University of Stuttgart was robotically fabricated from carbon and glass fiber composites and explored intersections between biomimetic design and digital fabrication. The project incorporated an integrated bottom-up design-and-making approach and invested a great deal in the material choice and development, form-finding, and fabrication techniques (Knippers, Jan et al. 2012).

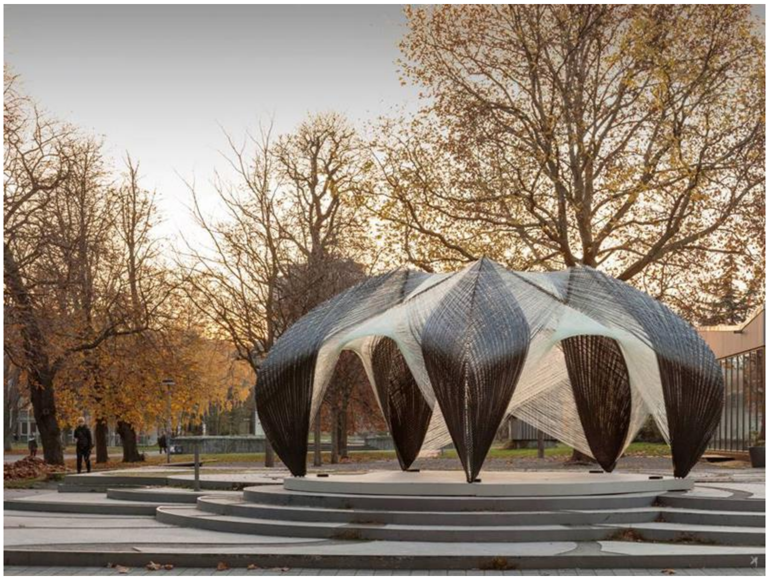

Figure 27: ICD/ITKE Research Pavilion 2012 (ICD-ITKE 2012).

Silk Pavilion

Silk Pavilion (2013) by MIT Media Lab's Mediated Matter Group is inspired by biological digital fabrication. For this project, extensive research was conducted on silk worms' weaving patterns and behavior under different environmental conditions. The results were used to digitally design and fabricate a base structure of woven thread which was then completed and reinforced by 6500 live worms on the structure (N. Oxman et al. 2017; Stott 2013).

Figure 28: Silk Pavilion by Mediated Matter Group in MIT (Keating 2013).

Ninety-Nine Failures

Ninety-Nine Failures is a research pavilion designed by students at the University of Tokyo Digital Fabrication Lab in 2013. The goal of Ninety-Nine Failures was to identify new research agendas and problems. A combination of mock-ups and digital simulation lead to the design for the pavilion. The pavilion is mainly made with thin, lightweight stainless-steel components (The University of Tokyo Digital Fabrication Lab 2014) .

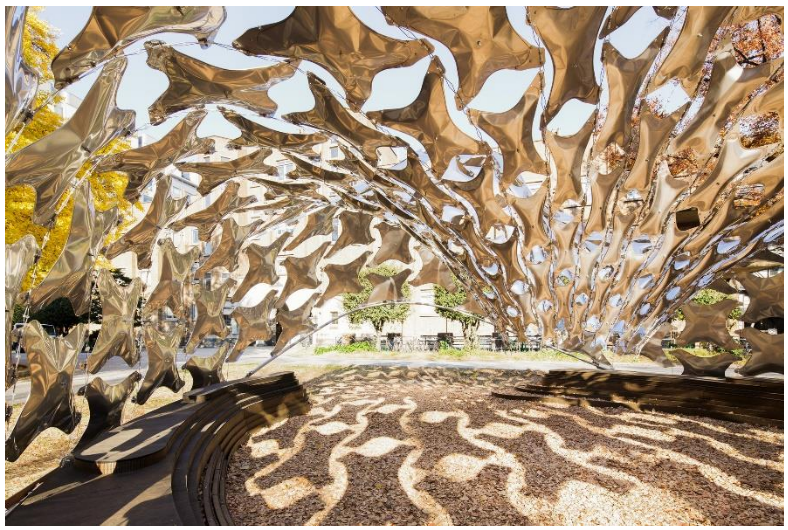

Figure 29: Ninety-Nine Failures by University of Tokyo (Wakabayashi 2013).

Remote Material Disposition

Remote material disposition (RMD) is a research project completed by ETH Zurich on robotic additive manufacturing. The project features an industrial robot that throws loam at designated areas from a distance. The robot is equipped with sensors and is able to scan the environment and control its actuator for material disposition. The project has a process-oriented approach and the fabrication process is essential in forming the final design. The final result is a robotically aggregated loam structure (Doerfler et al. 2014).

Figure 30: RMD Installation by ETH Zurich (Lyrenmann 2014).

Endesa World Fab Condenser

Endesa World Fab Condenser is a pavilion constructed with the concepts of sustainability and digital fabrication. Margen-lab designed the pavilion the 10th International Fab Lab Conference in Barcelona in 2014. Parametric modeling and passive climate strategies were influential in form-finding and material choice while CNC manufacturing was impactful in the fabrication process (Arch20 2014; Margen-lab n.d.).

Figure 31: Endesa World Fab Condenser (Goula 2014).

ICD Aggregated Pavilion 2018

The 2018 Aggregate Pavilion by ICD University of Stuttgart builds on over five years of research on the application of designed granular materials in architecture. The pavilion is a fully enclosed space fabricated from designed star-shaped granules. These particles are not bound to each other and only interact through friction contact. An industrial robotic arm was used for the in-situ fabrication of the pavilion (Dierichs and Menges 2016; ICD University of Stuttgart 2018).

Figure 32:ICD Aggregated Pavilion 2018 (ICD University Stuttgart 2018).

Keller AG Ziegeleien

Gramazio Kohler Architects designed and fabricated a brick façade for Keller AG Ziegeleien in 2015. The architects used their “ROBmade” technology—a robotic fabrication process to position and glue bricks in place—in fabrication of the façade. The façade was pre-fabricated in modules and were assembled with manual labor on the construction site (Kunkel 2015).

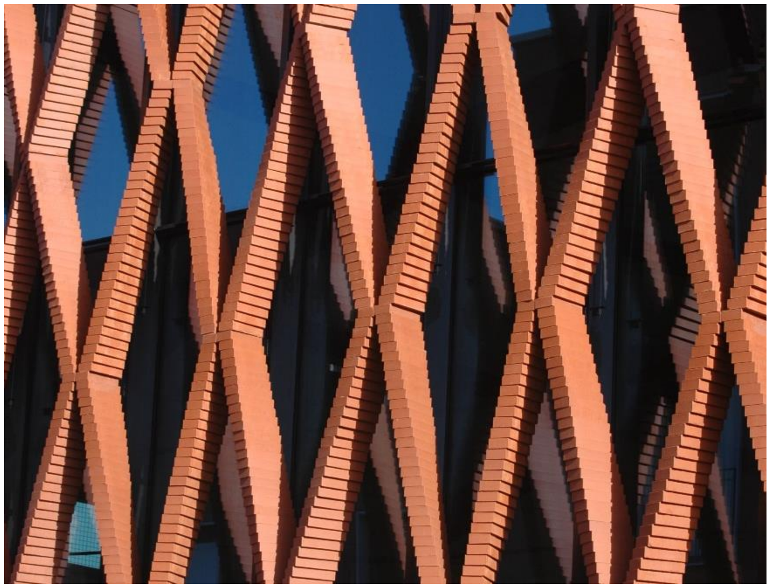

Figure 33: Keller AG Ziegeleien by Gramazio Kohler Architects (Gramazio Kohler Architects 2014).

ICD/ITKE Research Pavilion 2015-16

The research Pavilion (2015-16) by ICD/ITKE at University of Stuttgart explores robotic fabrication techniques for modular timber shell structures. The project has a bottom up design strategy and decisions are made through interaction with the materials, tools parametric modeling and simulation. Digital fabrication techniques, including CNC milling and robotic sewing, are used for pre-fabrication of modules (ICD-ITKE University of Stuttgart 2016).

Figure 34:ICD/ITKE Research Pavilion 2015-16 (ICD/ITKE University of Stuttgart 2016).

Rope Bridge

In 2015, Institute for Dynamic Systems and Control (IDS) in collaboration with Gramazio Kohler Research employed two drones equipped with motorized spools to autonomously construct a lightweight tensile bridge that could withstand the weight of a person. The bridge was made with a material light and strong material called Dyneema and span 7.4 meters between two scaffolding structures (Lavars 2015; Rosenfield 2015).

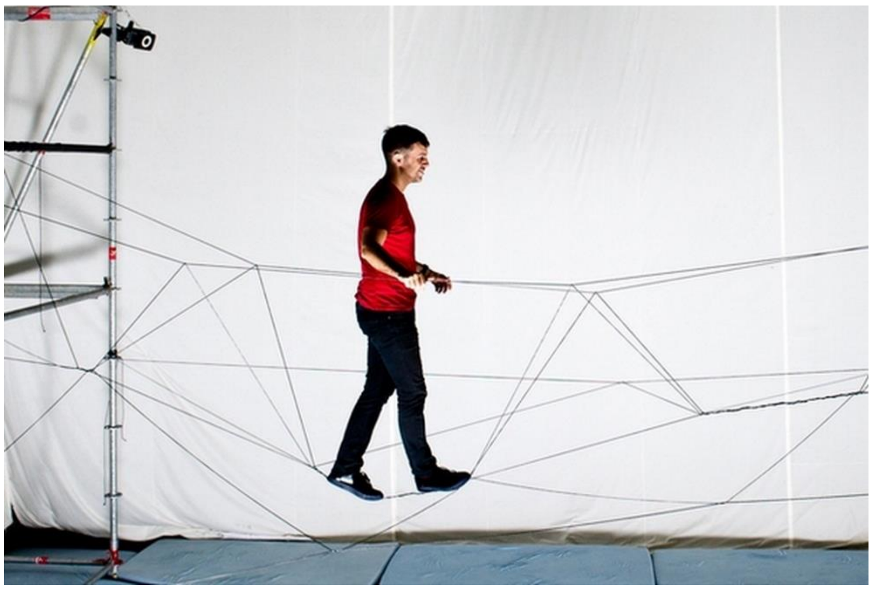

Figure 35: Rope Bridge by Gramazio Kohler Research and IDS (ETH Zurich 2015).

WoodChip Barn

WoodChip Barn (2016) is a research project about exploiting the natural properties of materials with irregular geometries for application in architecture. The project is designed and constructed by the Design + Make program at Architectural Association's Hooke Park Campus in the UK. Technologies like 3D scanning, and customized robotic fabrication, made WoodChip Barn possible through the evolutionary optimization of wood components placed within a structurally determined form (Mollica and Self 2016).

Figure 36: Woodchip Barn by Design + Make (Dezeen 2016).

ICD/ITKE Research Pavilion 2016/7

ICD/ITKE Research Pavilion 2016-17 at the University of Stuttgart is made with glass and carbon fiber-reinforced composites. The research builds on previous pavilions by the same team on fiber-reinforced structures. Fabrication tools including robotic industrial arms and unmanned aerial vehicles (UAV) were used in the fabrication of the pavilion. The research utilizes a bottom-up approach where factors including material behavior and property, tool capability and the multi-machine fabrication process inform the form and design of the pavilion (ICD-ITKE University of Stuttgart 2016).

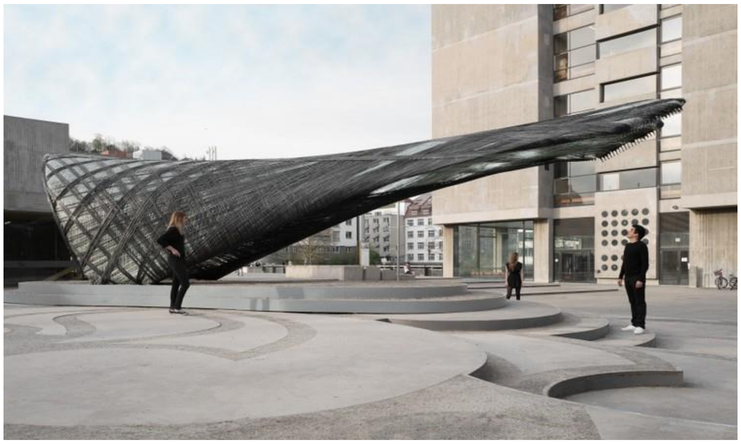

Figure 37: ICD/ITKE Research Pavilion 2016/7 (Burggraf / Reichert 2017).

Rock Print

‘Rock Print Pavilion’ is built on a research done by Gramazio Kohler Research, ETH Zurick and the Self-Assembly Lab at MIT. The project was a temporary installation in Winterthur in Switzerland. Rock Print Pavilion was made with loose granular rocks and textile filament fabricated in a human-machine collaborative system. A series of conventional columns were used to support the steel roof of the structure. A mobile industrial arm was used for in situ fabrication of the pavilion, where it positioned the filament, textile, and rocks layer by layer. The rocks were manually loaded to the robot. The Rock Pillars are three meters in height (Gramazio Kohler Research 2018; Stevens 2018; Saunders 2018).

Figure 38:Rock Print by Gramazio Kohler Research and MIT (Lio 2018).

Tongji University Bridge

Students from Tongju University used two different robotic fabrication techniques, metal 3D printing and filament winding, to construct an 11.4-meter-long bridge. Tongji University Bridge is a collaboration between Tongji University and the research studio Fab-Union. The bridge can safely bear approximately twenty people. The fabrication happened in two phases: first the metal frame of the bridge was 3D printed, then carbon and glass fibers were woven around the frame in the form of a web to build additional structural capacity (Boissonneault 2019; Sabina Aouf 2019).

Figure 39: Tongji University Bridge (Tian 2019).

Steampunk

Steampunk (2019) is a wooden pavilion made possible with the advancement of virtual reality tools in architecture. The project is a collaboration between Fologram—a virtual reality software company—Soomeen Hahm Design, and Igor Pantic with Format Engineers. Steampunk was pre-fabricated in a shop environment from steam-bent hardwood. The pavilion was designed in Rhino/Grasshopper, and Fologram was a key component in its fabrication. This project employed a process-oriented approach through which making and material experimentation led to many design and fabrication decisions. Conventional drawings and other typical fabrication techniques were not required in this project as Fologram was used as the main fabrication guideline and made fabrication with primitive hand tools possible (Paula Pintos 2019).

Figure 40:Steampunk Pavilion (Tunnel 2019.

Part 2- Project feature analysis

In this section, I analyzed the projects to find common features and trends between them in case of tools, fabrication and design techniques. I identify the features of the projects within four broad categories:

1) System elements (software and machines);
2) Fabrication location;
3) User/system relationship.
4) Emergence

Each broad category is broken into evaluation criteria. I chose these criteria based on their popularity and common usage in both industry and academia (Fig. 41).

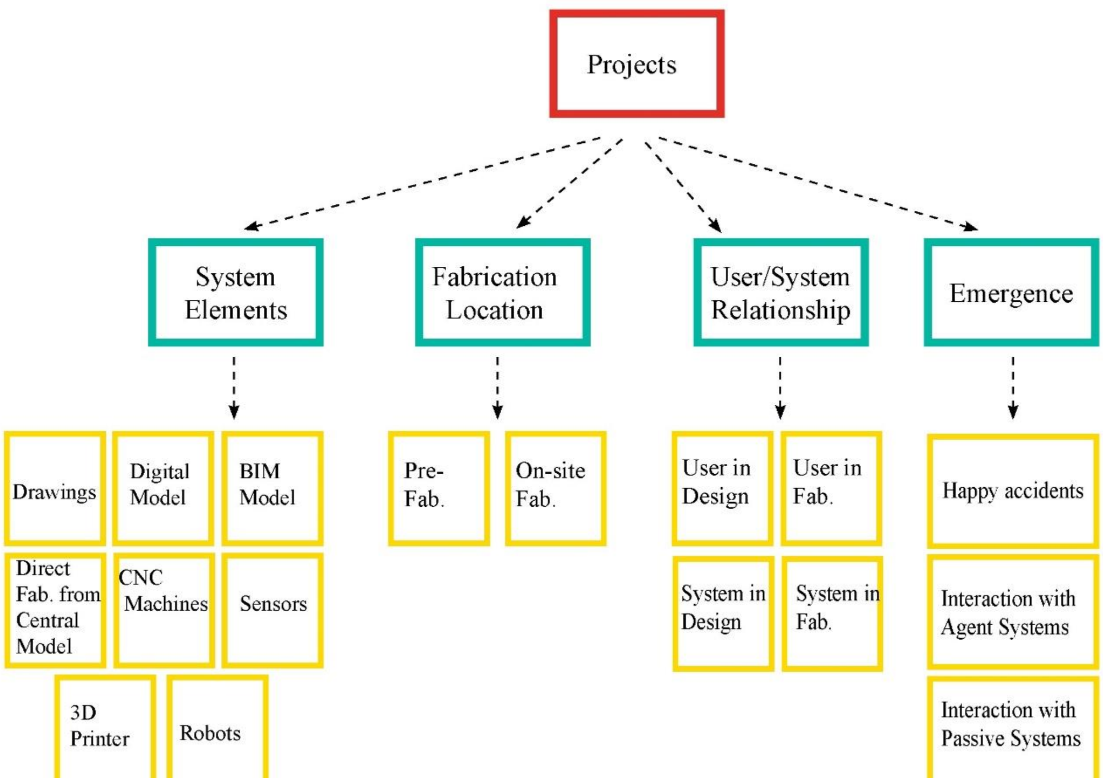

Figure 41: Project Features.

System Elements

System elements include both software and the tools and machines that are used in design and making. The system elements are as follows:

Conventional Drawings/detailing

Drawings are often created by designers and passed on to a separate team for fabrication/construction, so existence of conventional drawings can be an indication of a gap between design and making where different groups are in charge of tasks. drawing/detailing often informs construction, this category shows if the project has a conventional central control approach where design happens prior to construction.

Digital 3D Model

Most of the reviewed projects utilize a digital 3D model. A ‘yes’ answer to this question by itself does not mean that the project incorporates a traditional approach towards design. However, next to other criteria it could be a sign of pre-structured and pre-determined process. Architectural projects that do not include a digital model are rare to find—however, in a few cases, partial digital models have been used in which not every aspect of design is determined and the focus is on the process rather than the final product. In these projects, design unfolds through the fabrication process.

Building Information Modeling (BIM)

BIM models are an advanced and intelligent form of a 3D model-based process (Autodesk, 2020.) , which allow for coordination between different parties by including them into the process from early stages of a project. A BIM model could be a sign that data within a project is kept central and the communication and involvement of different parties has created the opportunity for better communication in a way that design and construction informed each other and did not happen separately.

Direct Fabrication from Main Model

In some cases, conventional 2D drawings have been eliminated from fabrication process and replaced by data generated from digital models. The data is fed to fabrication and construction tools like CNC machines, robotic arms, and augmented reality tools for making. In these systems, design and fabrication happen closer to each other since the tools run directly based on the information from the design model and the same person can perform both design and making. However, this system still functions primarily under the assumption that design happens prior to making. In many projects, for fabrication a separate model is generated based on the main model, this shows a break between design and making because of the existence of the medium fabrication/construction models. Only projects that do not use medium models and utilize their main (mother) digital model for fabrication, meet this category.

CNC and Laser Cutter

Computer Numerical Control (CNC) machines and laser cutters have been widely used in the AEC industry. These machines were incorporated earlier than many other digital fabrication tools, and have been widely used especially for pre-fabrication of architectural parts. Both machines work based on the data directly generated from digital models. The data for the machines is either directly taken from a central model or is based on a separate model specifically made for this task. This category needs to be evaluated next to other criteria like 'digital 3D model', 'direct fabrication from main model' and/or 'BIM model' in order to determine its effect on the general procedure.

3D Printers

Small 3D printers have become common in rapid prototyping and small-scale design modeling. In some projects large structures are broken down into smaller pieces to facilitate pre-fabrication of parts with small and medium 3D printers for assembly. Alternatively, large-scale 3D printers have been used in cases where the whole structure was pre-fabricated.

Robot

Over the past few decade, robots have been used more often in the AEC industry. In most cases, the robot is a six-axis industrial arm used either in factory or on construction site environments for additive manufacturing including brick laying and 3D printing. Like CNC machines, robots rely on data generated from digital models and narrow the gap between design and fabrication.

Augmented Reality/Virtual Reality

Augmented Reality (AR) and virtual reality (VR) have found their way to the AEC industry in the recent years. These tools are used for design, interactive fabrication and collaboration between different groups involved in a project. In some projects, AR and VR have been used as an alternative method for design and construction based on traditional drawings.

Sensors

Sensors allow tools/machines to collect data/input from users and the environment. Sensors enable interaction between users and tools/systems in a closed loop system. In some cases, the interaction happens in real time and this creates a set up in which the process evolves as the dialogue between users and the machines continues. The effectiveness of this criteria should be tested next to the type of tool and context. This is an important factor to evaluate system agency and user/system interaction level.

Fabrication Location

Fabrication location matters as it can be an indication of the tool/machine advancements and tool agency in the process. This factor needs to be considered in relation to others. This category is broken down as follows:

On site Fabrication

Often times, digital fabrication tools are not used on construction sites due to the unstable and dynamic situation of the sites. Utilization of these tools on construction sites is an indication of human-robot collaboration on the site as well as the use of smarter and more advanced tools.

Pre-fabrication

Pre-fabrication shows if digital fabrication tools are used in protected lab environments to create pre-fabricated components. In most cases pre-fabricated components are shipped to the site and installed in place. The location matters as pre-fabrication often means more control and human involvement in the process.

User/system relationship

The category is not solely about presence of human or digital fabrication tools in design and/or making, but rather is about their impact throughout the timeline. User/system relationship shows whether there is collaboration between users and the system, if design is formed through making with digital tools and highlights the areas where human and/or the system are effective and influential. Under User/system relationship there are four subcategories of 'user in design', 'system in design', 'user in fabrication' and 'system in fabrication'.

User in Design

The category shows if the human is involved and active during the design process. User in design, alongside "system in design", shows if there is interaction between the human and the system as the design is determined. In most projects, humans have an active role in designing.

System in Design

In many projects, fabrication tools are not impactful in design and only appear in making. In these projects design and making do not happen simultaneously and design informs construction/fabrication. However, in some projects making is an essential part of the design process and fabrication tools are integrated from the early stages of the process. These projects receive ‘Yes’ for ‘system in design’ and along with ‘user in design’ it is an indication of human-machine interactive collaboration in the design process.

User in fabrication

It is common for humans to be present during the fabrication process to either set up the system or to carry out the “making”. However, the level of presence varies depending on the type of tools and system set-up. This category does not discuss the level of presence, however alongside the “system in fabrication” category it indicates if there is interaction between user and their tools during fabrication and whether advanced types of collaboration between human and system were created.

System in fabrication

The category shows whether or not digital tools/systems were impactful in the design process. A “yes” in both this category and the “user in fabrication” category shows that there has been collaboration between the user and the system in making.

Emergence

Emergence is defined through the findings from chapter 2. If a project matches one of the four following criteria, it receives a “yes” in this section:

1- Glitch and happy accidents during making/fabrication.
2- Through an interactive/collaborative process between users and unintelligent systems.

3- Through an interactive/collaborative process between users and agent/intelligent systems.

Part 3- Human-system collaboration scale

In this section I created a scale representing the degree of collaboration within human-system creative scenarios. To define the scale, I identified three components that determine the degree of collaboration. Those components are (Fig. 42):

1- System integration
2- Simultaneity of design and making
3- System agency

For each group, the projects are assigned a score from one for low, two for medium and three for high. The elements as determined in study 2 are used to determine these scores.

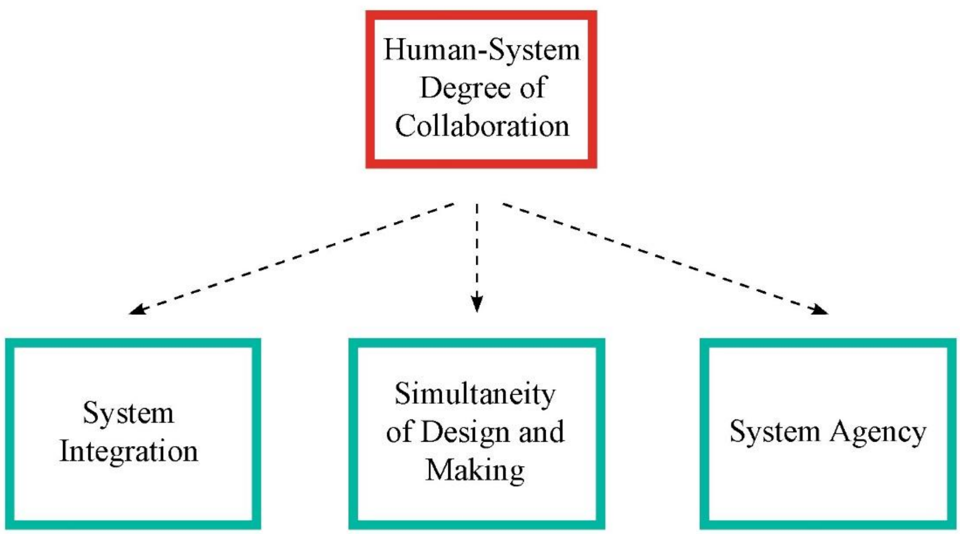

Figure 42:Human-system Collaboration Components.

System integration

System integration indicates the level in which digital fabrication tools have been successfully integrated in both design and making. Scores for this category are given based on the answers to ‘user/system’ item from Part 2. Scores are assigned based on the following:

1- A low score of 1 is given to a project that uses tools only in making, and not in design.
2- A medium score of 2- is given to a project that partially uses digital fabrication tools in both design and making.
3- A high score of 3 is given to a project that consistently uses digital fabrication tools in both design and making.

Simultaneity of design and making

This component represents the gap between design and making—a project with a reduced gap received a higher score. ‘System elements’ and ‘fabrication location’ from Part 2 determine the scores under this component.

1- A low score of 1 is given to projects that heavily rely on conventional 2D drawings or create multiple models used by separate groups for fabrication.
2- A medium score of 2 is given to projects that reduce the need for conventional drawings but use digital fabrication tools for pre-fabrication. Projects that reduce the need for conventional 2D drawings must rely on a 3D or BIM model, which requires the incorporation of fabrication machines. Projects that use a central model for different stages of design and digital making also receive a medium score.

3- A high score of 3 is given to projects that reduce/remove the need for conventional drawings and incorporate digital fabrication tools on construction sites.

System Agency

System agency describes the degree of self-determination the system is capable of. For the system to have self-determination, it must either have a level of intelligence or be equipped with sensors that allow it to receive input from users and the environment and react or provide feedback.

1- A low score of 1 is given to projects that do not incorporate any sensors or intelligence for the system.
2- A medium score of 2 is given to projects that incorporate sensors in limited areas and system has partial agency.
3- A high score of 3 is given to projects that incorporate sensors in the system and the system is not fully controlled.

The scores in these three categories are summed up for each project to determine each project's degree of collaboration.

<u>Part 4 Identification of trends</u>

In part 4, I used the results from part 3 to generate graphs to find trends over time and based on the projects' scale. The data is presented in four graphs. The first two graphs show a relationship between time and the degree of human-system collaboration as defined in part 3, for both large and medium-scale projects. Two other graphs, show the projects' total human-system collaboration score relative to their sub-scores of System Integration, Simultaneity of design and making, and System Agency as defined in part 3 of this chapter.

Chapter IV: Results and Analysis

This chapter, analyzes and presents the results from the study described in chapter 3. The results are presented in form of tables and diagrams to illustrate trends over time and in relation to another.

In parts 1 and 2 of the study, project analysis is performed to identify and understand project features in the three areas of 1) system elements, 2) fabrication location, 3) user-system interaction and 4) emergence. The results from both parts are shown in Tables 1 and 2. Each table includes twenty projects sorted according to completion date. Table 1 shows the selected large-scale projects, and Table 2 shows the medium-scale projects. On both tables, the last row of each category lists the percentage of positive response.

In system elements, the top two fabrication tools overall are CNC and robots. Among large-scale projects, 65% use CNC machines, followed by robots at 45%. Medium-scale projects are the reverse: robots are the most common tools, used in 60% of projects. VR and AR tools are the least commonly used, with no large-scale projects, and only one medium-scale project. At medium-scale, 40% of the tools are equipped with sensors or other equipment and have some level of agency, in comparison to large-scale projects where only 5% of the projects have similar features. All projects at both scales rely heavily on digital models, but traditional drawings are used only in 40% of medium-scale projects. This shows a significant shift in medium-scale projects, where digital tools and 3D models are replacing 2D drawing packages and other traditional methods. At both scales, the majority of projects use central digital models for direct digital fabrication, although this percentage is significantly higher in medium-scale projects (95%) compared to large-scale (50%).

Table 1: Large-scale Projects.

			System Elements									Fabrication Location		Human-system interaction				Emergence	
	Large Scale Projects	Year	Drawings	Digital Model	BIM Model	Direct Fabrication from Central Model	CNC Machines	Sensors/ feedback	3D Printer	Robots	VR/AR	On-site digital fabrication	Pre-fabrication	User in Design	User in fabrication	System in Design	System in fabrication	Emergence	Type of Emergence
1	**Bubble**	1999	Yes	Yes	No	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
2	**Teatro Petruzzelli's Dome**	2008	Yes	Yes	No	No	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
3	**290 Mullberry**	2009	Yes	Yes	Yes	No	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	Yes	2
4	**O-14 Tower**	2010	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
5	**Gatehouse**	2010	Yes	Yes	No	No	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
6	**Spencer Dock Bridge**	2010	Yes	Yes	No	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
7	**Art Gallery of Alberta**	2010	Yes	Yes	Yes	No	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
8	**Perot Museum**	2012	Yes	Yes	Yes	No	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	Yes	2
9	**Landesgartenschau Exhibition Hall**	2014	Yes	Yes	No	Yes	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	2
10	**Petersen Museum**	2014	Yes	Yes	Yes	No	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
11	**The Global Center for Health Innovation building**	2014	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	2
12	**Shanghai arts centre**	2017	Yes	Yes	No	Yes	No	No	No	Yes	No	Yes	No	Yes	Yes	No	Yes	No	N/A
13	**Triple S**	2017	Yes	Yes	No	No	No	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	1&2
14	**MX 3D Bridge**	2018	No	Yes	No	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	No	N/A
15	**St Mary Chapel**	2018	Yes	Yes	Yes	No	No	No	No	Yes	No	No	Yes	Yes	Yes	No	Yes	No	N/A
16	**Venus B Conference Hall**	2018	Yes	Yes	No	No	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	No	N/A
17	**Inkstone House Cultural Centre**	2018	Yes	Yes	No	No	No	No	No	Yes	No	No	Yes	Yes	Yes	No	Yes	No	N/A
18	**DFAB House**	2018	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1&3
19	**Dubai Municipality Building**	2019	Yes	Yes	No	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	2
20	**Delas Frères Winery**	2019	Yes	Yes	No	Yes	No	No	No	Yes	No	No	Yes	Yes	Yes	No	Yes	No	N/A
	Percentage		**0.95**	**1**	**0.35**	**0.5**	**0.65**	**0.05**	**0.25**	**0.45**	**0**	**0.15**	**0.95**	**1**	**1**	**0.25**	**1**	**0.3**	

Table 2: Medium-scale Projects.

		System Elements										Fabrication Location		Human-system interaction				Emergence	
	Medium Scale Projects	Year	Drawings	Digital Model	BIM Model	Direct Fabrication from Central Model	CNC Machines	Sensors/ feedback	3D Printer	Robots	VR/AR	On-site digital fabrication	Pre-fabrication	User in Design	User in fabrication	System in Design	System in fabrication	Emergence	Type of Emergence
1	**Fish Sculpture**	1992	No	Yes	No	Yes	No	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
2	**D-Tower**	2003	Yes	Yes	No	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
3	**ArboSkin Pavilion**	2003	Yes	Yes	No	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
4	**Winery Gantenbein**	2006	No	Yes	No	Yes	No	No	No	Yes	No	No	Yes	Yes	Yes	No	Yes	No	N/A
5	**Radiolaria Pavilion**	2008	No	Yes	No	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	No	Yes	Yes	N/A
6	**One Main**	2009	Yes	Yes	No	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
7	**ICD/ITKE Research Pavilion 2012**	2012	No	Yes	No	Yes	No	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	2
8	**Silk Pavilion**	2013	No	Yes	No	Yes	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	3
9	**Ninety Nine Failures**	2013	Yes	Yes	No	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	Yes	2
10	**Remote Material Disposition**	2014	No	Yes	No	Yes	No	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	3
11	**Endesa World Fab Condenser**	2014	Yes	Yes	No	No	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	N/A
12	**Keller AG Ziegeleien**	2015	Yes	Yes	No	Yes	No	No	No	Yes	No	No	Yes	Yes	Yes	No	Yes	No	N/A
13	**Rope Bridge**	2015	No	Yes	No	Yes	No	Yes	No	Yes	No	No	Yes	Yes	Yes	No	Yes	No	N/A
14	**ICD/ITKE Research Pavilion 2015-16**	2016	Yes	Yes	No	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	2
15	**WoodChip Barn**	2016	Yes	Yes	No	Yes	No	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	2
16	**ICD/ITKE Research Pavilion 2016/7**	2017	No	Yes	No	Yes	No	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	2
17	**ICD Aggregated Pavilion**	2018	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	3
18	**Rock Print**	2018	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	1
19	**Tongji University Bridge**	2019	No	Yes	No	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	No	N/A
20	**Steampunk**	2019	No	Yes	No	Yes	No	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	2
	Percentage		**0.4**	**1**	**0**	**0.95**	**0.35**	**0.4**	**0.1**	**0.6**	**0.05**	**0.1**	**0.95**	**1**	**1**	**0.45**	**1**	**0.55**	

In general, the results from 'system elements' show that in large-scale projects there is a tendency to use more familiar tools in fabrication like CNC machines that have been around for a few decades. These numbers are understandable considering the complexity of projects in this category and the need for precision in the architectural process. Also, a low score of 5% in 'sensors' might be an indication that tools are used passively for accuracy in fabrication, compared to medium-scale projects where a higher percentage of projects are equipped with sensors so they are able to actively participate in the process. That 35% of large-scale projects utilize BIM shows an integrated and more centralized design and construction approach, while the 0% of medium-scale projects with BIM is explained by the inapplicability of BIM functions to projects at that scale. The high percentage of medium-scaled projects (95%) in 'direct fabrication from a central model' indicates a more seamless design to fabrication compared to large-scale projects. Among large-scale projects, 50% are directly fabricated from a central model, so in a significant number of these projects the designer is disconnected from fabrication/construction activities.

In the fabrication location category, both scale categories favor pre-fabrication to on-site digital fabrication. 95% percent of both medium-scale and large-scale projects use pre-fabrication. In medium and large-scale projects, 10% and 15% respectively use digital fabrication tools on-site, and only one large-scale project uses a combination of pre-fabrication and on-site fabrication. At both scales, the projects that have used digital tools on construction sites are less than five years old and have employed robots. The DFAB house is the only large-scale project to use robots equipped with sensors. This indicates that the tools are used for their precision and accuracy in completing complex construction tasks and pre-determined designs.

Medium-scale projects integrate digital tools in design impactfully at 45%, compared to large-scale projects where only 25% do. For all other sub-categories of human-system interaction including 'user in design', 'user in fabrication' and 'system in fabrication', 100% of projects at both scales utilize them. These numbers show that in majority of the studied projects, a fundamental part of design happens prior to fabrication/construction.

As shown in tables 1 and 2, emergence is almost twice as common in medium-scale than in large-scale with 55% and 30% respectively. In the ‘type of emergence’ column, projects receive numbers from 1 to 3, referring to the type of emergence per the description in chapter 3. A majority (85%) of the large-scale projects with emergence receive a ‘2’, which means they have achieved emergence through ‘interaction with an interactive/collaborative process between users and unintelligent systems’. Two projects (28%) show emergence in more than one category. In large-scale projects only the DFAB House receives emergence through ‘interactive/collaborative process between users and agent intelligent systems’. This can be explained by the overall low percentage of ‘sensors/feedback’ in large-scale projects. Similar to large-scale projects, in the medium-scale category a majority of the projects receive emergence through interaction with unintelligent system at 60%. At 30% the percentage for emergence through interaction with intelligent systems is higher than the same category for large-scale. No medium-scale projects receive emergence in more than one category and only one project shows emergence at the ‘happy accidents during making/fabrication’ category.

Tables 3 and 4 show the results from part 2 of the study. In part 2, projects receive scores based on 1) system integration, 2) simultaneity of design and making and 3) system agency. These scores are summed to achieve a combined *Human-System collaboration score*, which represents the projects’ degree of human-system collaboration in design and making. Table 3 show the results for the large-scale projects described in Table 1, and Table 4 shows the medium-scale projects from Table 2. The last row of Tables 3 and 4 show the average score in each category.

In all four categories, medium-scale projects receive a higher average score than large-scale projects. The largest difference is in ‘system integration’ where medium-scale projects receive 2.3 average score; 58% higher than the large-scale projects. System agency’s average score in the medium group is 1.35, which is 28% higher than medium-scale at 1.05. The average for 'simultaneity of design and making' is 1.7 for large-scale and 2.05 for medium-scale projects. The average human-system collaborative scores for medium and large-scales are 5.75 and 4.2 respectively.

Table 3 Large-scale Projects. Human-System Collaboration Score

			Min:1, Max: 3	Min:1, Max: 3	Min: 1, Max 3	Min: 3, Max 9
	Large Scale Projects	Year	System integration	Simultancity of design and making	System Agency	Human-System Collaboration Score
1	Bubble	1999	1	2	1	4
2	Teatro Petruzzelli's Dome	2008	1	1	1	3
3	290 Mullberry	2009	2	1	1	4
4	O-14 Tower	2010	1	2	1	4
5	Gatehouse	2010	1	1	1	3
6	Spencer Dock Bridge	2010	1	2	1	4
7	Art Gallery of Alberta	2010	1	1	1	3
8	Petrot Museum	2012	2	1	1	4
9	Landesgartenschau Exhibition Hall	2014	2	2	1	5
10	Petersen Museum	2014	2	1	1	4
11	The Global Center for Health Innovation building	2014	2	2	1	5
12	Shanghai arts centre	2017	1	3	1	5
13	Triple S	2017	3	2	1	6
14	MX 3D Bridge	2018	1	2	1	4
15	St Mary Chapel	2018	1	1	1	3
16	Venus B Conference Hall	2018	1	2	1	4
17	Inkstone House Cultural Centre	2018	1	2	1	4
18	DFAB House	2018	2	2	2	6
19	Dubai Municipality Building	2019	2	3	1	6
20	Delas Frères Winery	2019	1	1	1	3
	Average		1.45	1.7	1.05	4.2

As the numbers show, 'system integration' is the most influential factor in the difference between the scores received by both scales in 'human-system collaborative score'. 'System integration' indicates successful attempts at integration of digital fabrication tools into both design and making processes. This means that projects that received a higher score did not necessarily use the most advanced and cutting-edge technologies, but did structure their process to utilize a model where design and making happened more closely. For example, in the project 'the Global Center for Health Innovation building', the simple digital fabrication tools like CNC machines and 3D printers that are used are not equipped with advanced sensors or feedback loops. However, since these tools are used for prototyping and decision making in the design phase, they are well integrated in the process and create a more seamless design to making transition. Medium-scale projects receiving a higher score in 'system integration' is understandable because these projects are fundamentally focused on research and exploration of new models and methods.

Table 4: Medium-scale Projects. Human-System Collaboration Score.

			Min:1, Max: 3	Min:1, Max: 3	Min:1, Max: 3	Min: 3, Max 9
	Medium Scale Projects	**Year**	**System Integration**	**Simultaneity of Design and Making**	**System Agency**	**Human-System Collaboration Score**
1	**Fish Sculpture**	1992	1	2	1	4
2	**D-tower**	2003	2	2	1	5
3	**ArboSkin Pavilion**	2003	2	2	1	5
4	**Winery Gantenbein**	2006	2	2	1	5
5	**Radiolaria Pavilion**	2008	3	2	1	6
6	**One Main**	2009	1	2	1	4
7	**ICD/ITKE Research Pavilion 2012**	2012	3	2	1	6
8	**Silk Pavilion**	2013	3	2	3	8
9	**Ninety Nine Failures**	2013	2	2	1	5
10	**Remote Material Disposition**	2014	3	2	2	7
11	**Endesa World Fab Condenser**	2014	1	1	1	3
12	**Keller AG Ziegeleien**	2015	2	2	1	5
13	**ICD/ITKE Research Pavilion 2015-16**	2015	3	2	1	6
14	**Rope Bridge**	2015	2	2	2	6
15	**WoodChip Barn**	2016	2	2	2	6
16	**ICD/ITKE Research Pavilion 2016/7**	2017	3	2	2	7
17	**ICD Aggregated Pavilion**	2018	3	3	2	8
18	**Rock Print**	2018	3	3	1	7
19	**Tongji University bridge**	2019	2	2	1	5
20	**Steampunk**	2019	3	2	1	6
	Average		**2.3**	**2.05**	**1.35**	**5.7**

Figures 43 and 44 show timelines of large and medium-scale projects relative to each project's Human-System Collaboration Score. In both diagrams, the horizontal axis shows the completion year and the vertical axis indicates the overall human-system collaboration degree for each project. The vertical axis is divided into 3 sections of low, medium and high. Figure 44 shows that there is a general increase in scores over time. There is a relative increase in the score of medium-scale projects as well, however, it is to a lesser degree compared to large-scale projects. However, medium-scale projects in

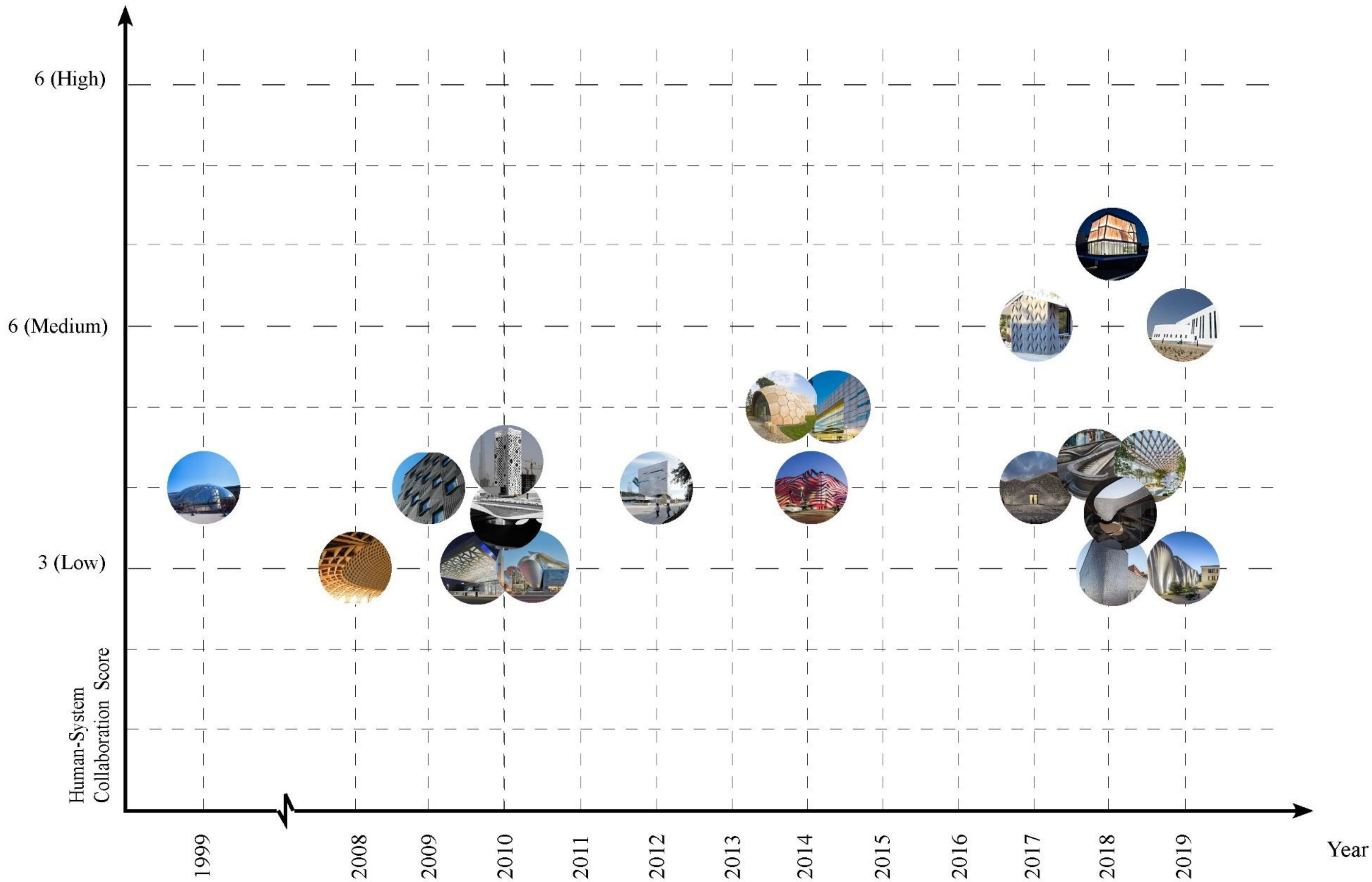

Figure 43:Large Scale Projects- Timeline.

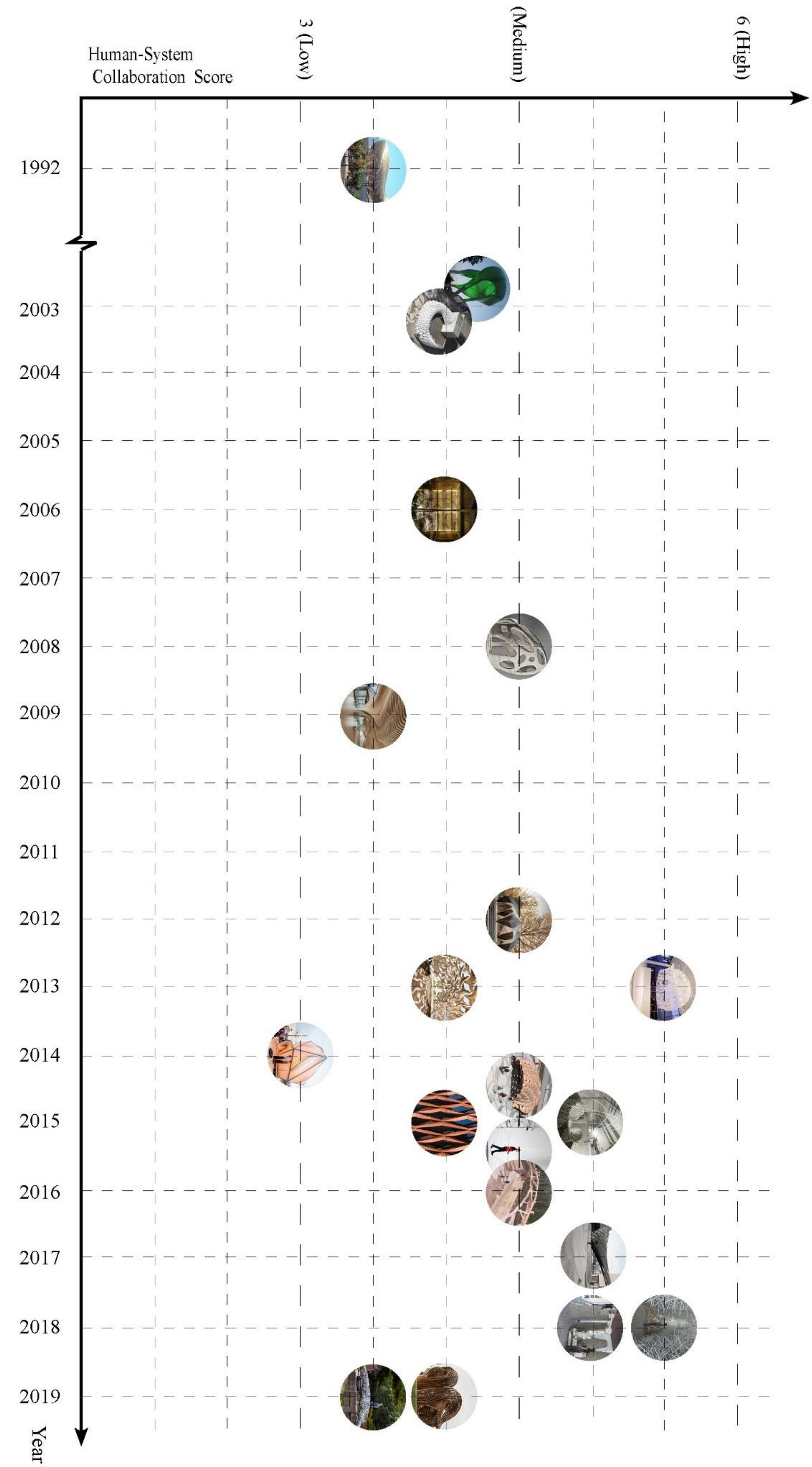

Figure 44: Medium-scale Projects- Timeline.

average have higher score than large-scale projects, with only one project on the low bar. Large-scale projects do not only increase in their human-system collaboration score—applicable large-scale projects also become more frequent. This is not true of medium-scale projects, which have a relatively even frequency. This difference could be due to large-scale construction growing more familiar with digital tools and accustomed to incorporating them into project workflows.

Figures 45 and 46 show the general score of each project in relation to their sub-scores on system integration, design and making simultaneity and system agency. The projects on the horizontal bar are sorted from low to high score. In both figures, projects identified to develop emergence are shown in green.

Figures 45 and 46 show that emergence is more common among projects with higher 'human-system collaboration score'. Per the figures, in large-scale projects 'tool agency' has the least contribution in the scores received by these projects. However, in medium-scale majority of the projects with emergence, received a 2 or 3 score for 'tool agency'. This shows that unlike the 'human-system collaboration score', 'emergence' is influenced by technological advancements and tool agency. The majority of the projects with emergence at medium-scale have a total score of 6 or above and the emergence is seen in projects with scores as low as five. For large-scale, only half of the projects with emergence receive a total score of 6 or above and the other half receive scores as low as 4.

In both medium and large categories, the only project that receives a 3 score in 'tool agency' is the Silk Pavilion, due to the non-human agents involved in the project. In the medium-scale category, the majority of projects with total score of 6 get their boost in score from 'system integration', while at the large-scale the boost comes from 'simultaneity of design and making'. This is an indicative of consistency in using digital fabrication tools in both design and making in medium-scale projects, and higher utilization of digital fabrication tools on construction sites for large-scale projects.

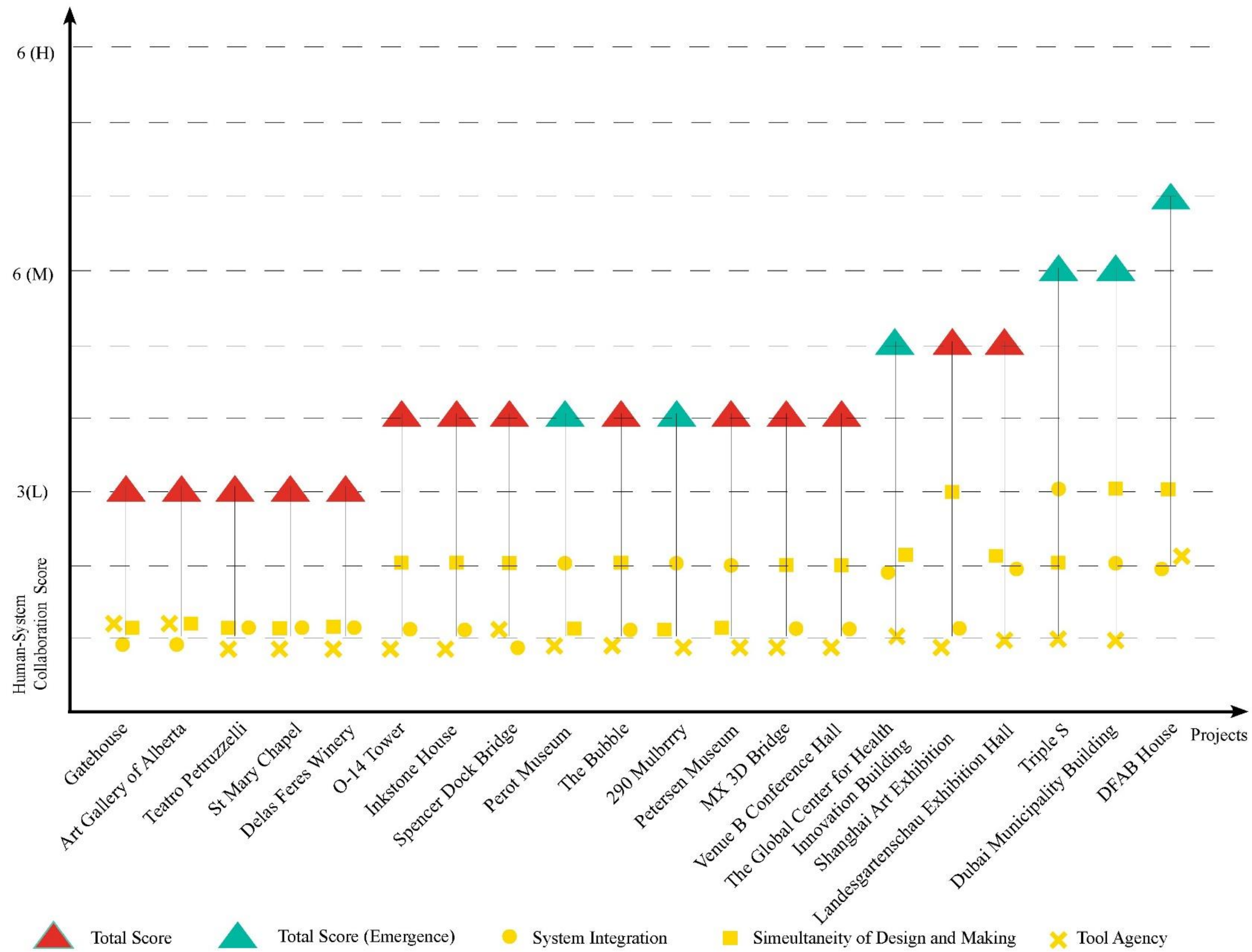

Figure 45: Large Scale Projects. Human-System Collaboration Score in relation to the sub-scores.

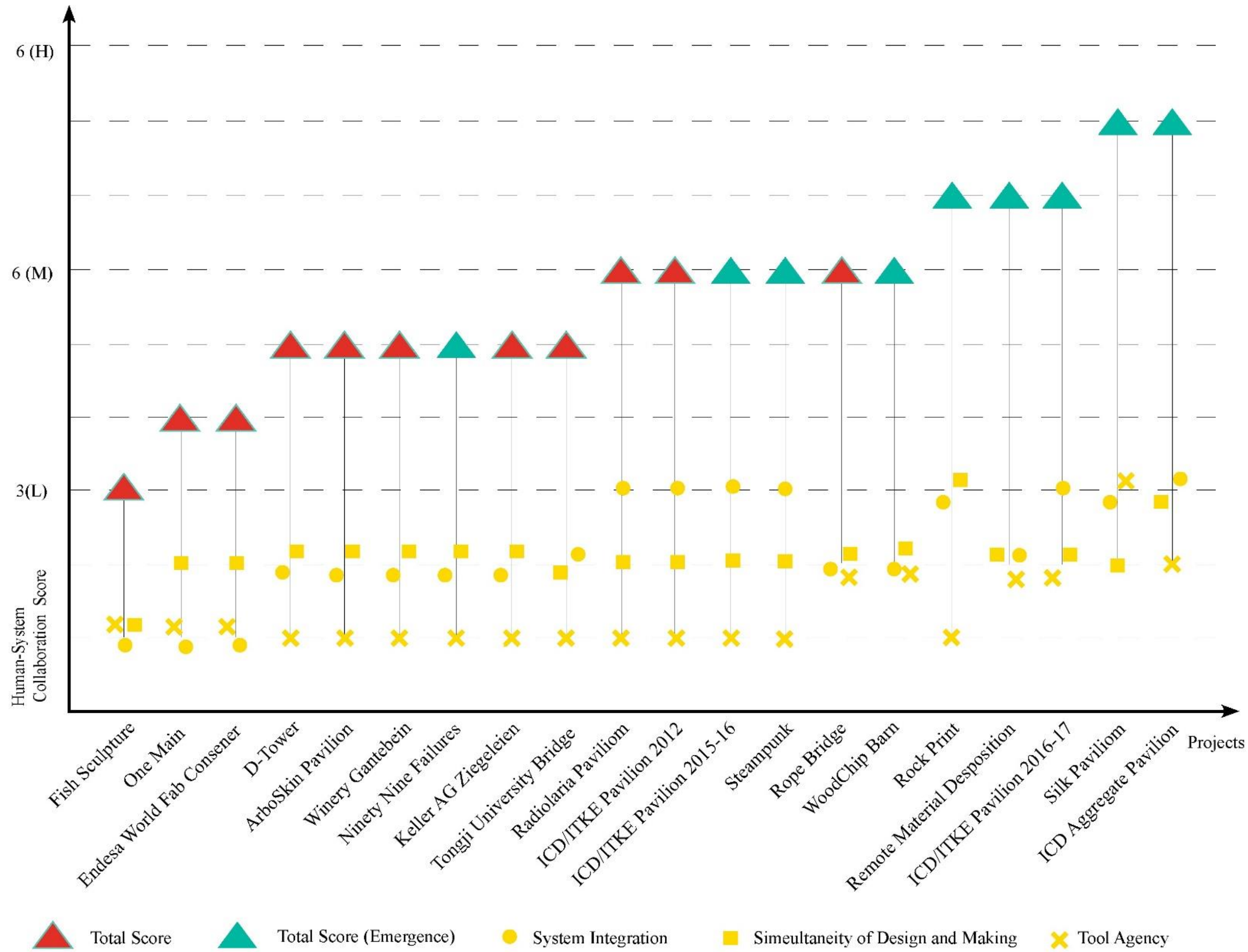

Figure 46: Medium-scale Projects. Human-System Collaboration Score in relation to the sub-scores.

Chapter V- Case Studies

This chapter provides an in-depth analysis of five case study projects and explains how the projects can be studied according to variables that were previously defined in chapter 3. These projects are selected from both large-scale and medium-scale categories.

The medium-scale projects selected are Silk Pavilion, Remote Material Disposition and the large-scale projects are the DFAB House, Dubai Municipality Building, and The Global Center for Health Innovation building.

Large-scale Projects

The Global Center for Health Innovation building

The Global Center for Health Innovation building (2014), designed by LMN is located in Cleveland, Ohio and resembles a floating cube. The building was designed around the concepts of indoor-outdoor connection and defines a transition from a civic scale public park to a neighborhood scale. The description of this project is based on research collected from LMN's website (LMN 2020) and the Architectural Record website (Litt 2014).

Figure 47: The Global Center for Health Innovation building (LMN 2020).

Description

The project features a glass podium and atrium beneath a levitating mass. Pre-fabricated concrete panels are used for the building enclosure. For fabrication of the façade panels, LMN chose CNC milling as a suitable fabrication technique due to its flexibility, cost-effectiveness, and availability. Through a combination of physical prototyping, daylight and energy simulation, and parametric modeling in Grasshopper, LMN made design decisions on the panel's form, placement, and design. The designers developed plug-ins to transfer the information from Grasshopper to their BIM model and kept the data central and accessible to everyone involved in the project.

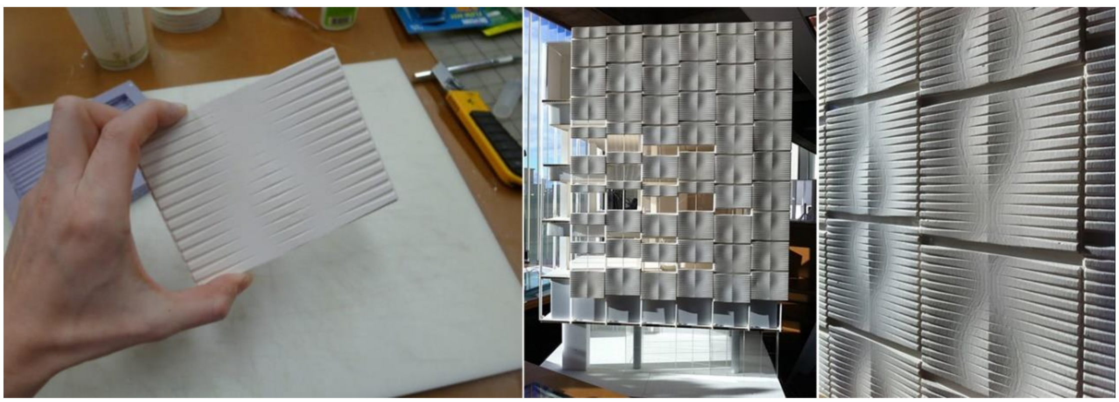

Figure 48: Rapid prototyping for the design of the concrete panels (LMN 2020).

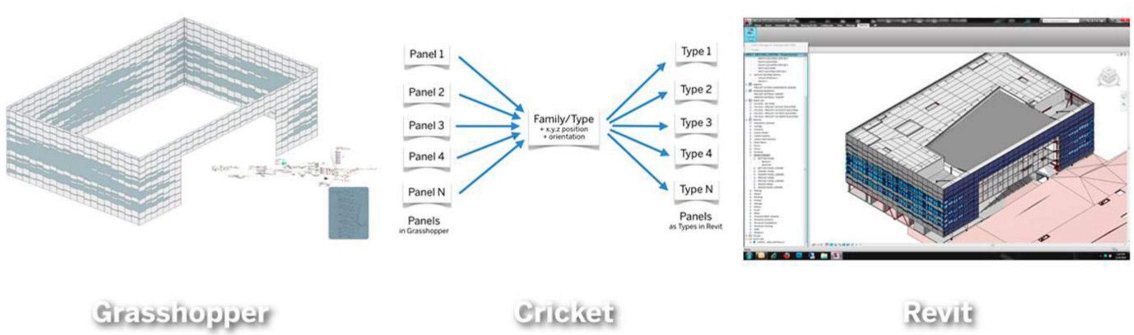

Figure 49: 'Cricket' a plug-in for translating design from Grasshopper to BIM (LMN 2020).

In the fabrication of the façade panels, LMN worked closely with the fabricators to develop the form-liners for casting the concrete panels. The designers used their in-house laser cutter and 3D printers for rapid prototyping and in-house testing. Through this interactive, direct-to fabrication process, LMN was able to create precise digital fabrication files that were eventually used by the fabricator for the production of the panels. The designers incorporated new technologies from early design to construction, to facilitate collaboration and efficient delivery.

Figure 50: Fabrication of rubber form liners (LMN 2020).

Analysis

The Global Center for Health Innovation building is not revolutionary in its design and construction techniques. In this project, like most large-scale projects, the design-making model is only used in limited sections of the building and is not easily applicable to other sections. For this project, digital fabrication tools were only used in design realization and fabrication of the façade panels. Also, digital fabrication tools were used passively and in pre-fabrication of building components.

Where the project excels is in the integration of digital fabrication tools in early design decision making and through design, coordination, and construction. This success is due to the team's ethos of incorporating making throughout design. The suite of digital fabrication tools used on this project, including CNC fabrication, BIM, parametric modeling, and prefabrication techniques can be seen in many projects, but most do not use tools as intentionally or in all phases. For example, in projects earlier discussed in this thesis like the Perot Museum, Petersen Museum, and the Venue B conference Hall, a similar set of tools and techniques is employed, but the designers are removed from the construction phase and do not take part in the making of the building. In these projects, based on the initial design model, the fabricators create their own model for construction purposes. However, LMN's integrated approach maintains the information centrally and keeps the designers directly involved in the generation of fabrication files. LMN does it by reducing the number of involved parties between design and construction and by keeping design models to a minimum number.

LMN's design-making method reduces the distance between design and construction by involving the architects in post-design phases. Although this method does not entirely transform the prevailing architectural models in the industry, it is a good example of how tools can be more effectively and successfully utilized towards a more integrated design-making model.

DFAB House

The DFAB house (DFAB House 2020) is one of the few examples where multiple digital construction technologies have been applied on construction sites. The structure is located on the third (upper) platform of the NEST building in Empa in Dübendorf. The NEST building is a central building core which provides a platform where different research building units are constructed. The project was a collaboration between ETH Zurich and industrial partners under the framework of the National Center of Competence in Research (NCCR) Digital Fabrication, a Swiss National Science Foundation research program. The focus has been on automation and precision of construction tasks using in situ digital construction.

Figure 51: DFAB House (Keller 2019).

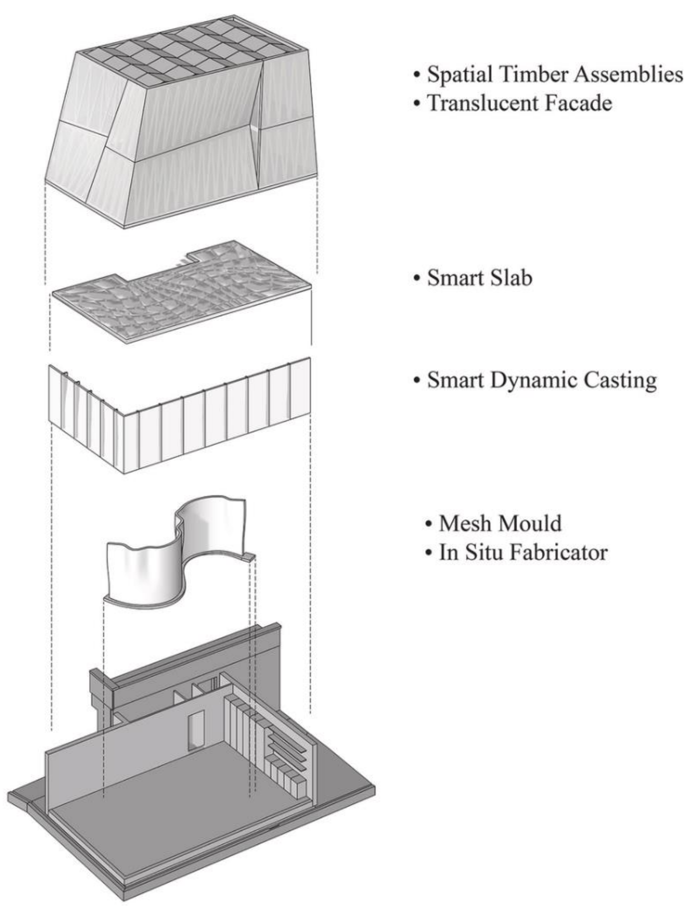

Figure 52: Axonometric Exploded Diagram of the DFAB House (Hack 2018).

Description

Technologies like Robotic In situ Fabricator, Mesh Mould, Smart Dynamic Casting, Smart Slab and Robotic Spatial Timber Assembly were used in construction of the DFAB house. The house includes a fabrication-aware computational design. A combination of structural, material and fabrication knowledge determine and inform the design of the DFAB House (DFAB House 2020).

The Mesh Mould technology was used to construct a double curved wall located on the first floor of the building. The description on the Mesh Mould technology is based on the research paper 'Mobile robotic fabrication beyond factory conditions: case study, Mesh Mould wall of the DFAB House' by Dorfler et al. (Dörfler et al. 2019). An in situ autonomous robot was used for construction of the steel reinforcement mesh, which was used for both formwork and reinforcement of the wall. The robot is called the In situ Fabricator (IF). IF is equipped with a customized end effector to fabricate the steel rebar. The robot's development started in 2011 in Gramazio Kohler Research lab and in collaboration with NCCR Digital Fabrication. IF is mobile and is equipped with sensors that make it responsive to the changing conditions of construction sites. IF has been tested on multiple previous projects and has demonstrated viability for in situ construction scenarios. The sensing system includes three cameras at the end effector that enable the adaptive fabrication strategy. One camera is used for the robot's global localization on the site by building site mapping while the other two cameras are for local fabrication survey of the rebar mesh for in-process fabrication.

The double-curved wall has a monolithic and non-standard structure. The term Mesh Mould is used to refer to the monolithic and non-standard reinforced concrete walls. IF constructed the double-sided hollow steel rebar mesh in vertical layers in a human-machine collaborative process: while the In situ Fabricator assembled the mesh structure, manual labor was used to fill the structure with concrete to finish the structure. Also, after the robotic process was completed, the steel mesh needed to be manually reinforced in certain areas.

Figure 53: IF fabricating the double curved wall in the DFAB House (Dezeen 2017).

The Smart Slab was pre-fabricated using 3D sand printing technology and was installed on top of the double curved wall. The information on the Smart Slab technology is from the paper 'Smart slab: Computational design and digital fabrication of a lightweight concrete slab' by Meibodi et al (Meibodi et al. 2018). The slab is divided into eleven 7.4-meter-long sections. The form of the slab is optimized to support the load of the two-story timber unit above it while reducing the amount of material needed. Sand 3D printing was used for construction of the formwork. The design team developed a planning software for form-finding which allowed for integration of fabrication parameters into the process from early stages. The software also automated detailing, generation of fabrication data, and optimization of the slab design. Although, digital fabrication tools were essential in fabrication of the slab, it was not fully automated and was labor intensive.

Figure 54: 3D printed formwork for prefabrication of the slab in the DFAB House (Jipa 2018).

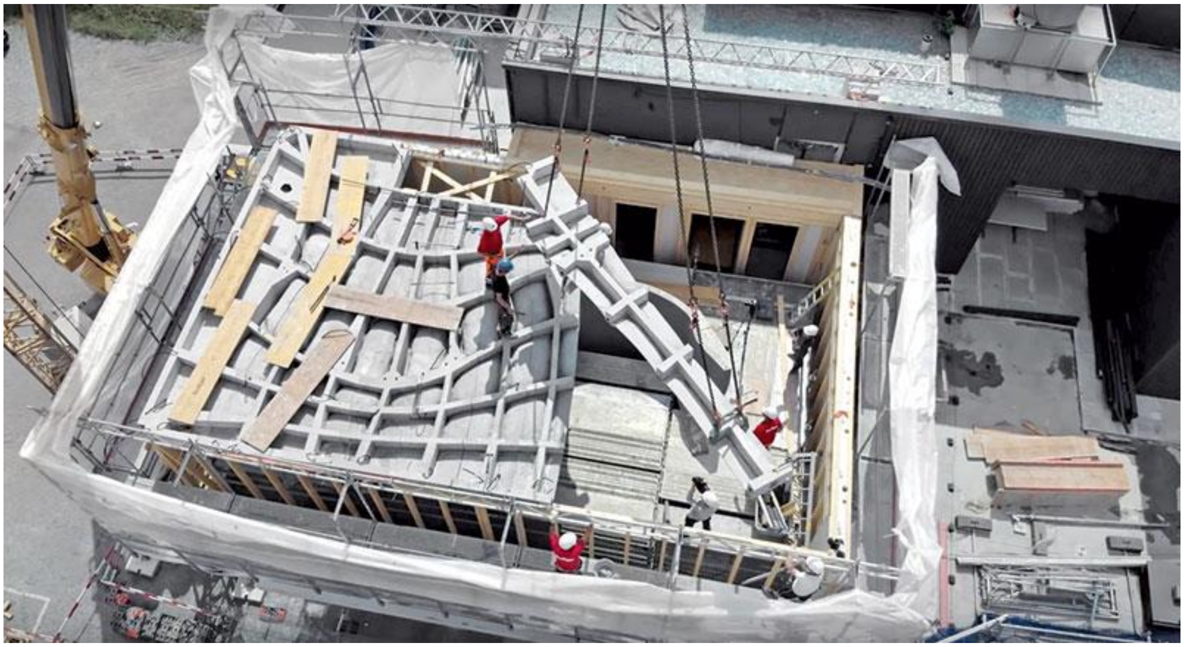

Figure 55: DFAB House- Slab installation (Jipa 2018).

The façade mullions at the first floor were made using Smart Dynamic Casting (SDC) technology that allowed for production of mullions with changing cross sections. The description on the SDC is based on the information by NCCR Digital Fabrication (NCCR Digital Fabrication 2020). In the SDC system, one formwork can be used to fabricate a three-meter mullion. A total of fifteen mullions are cast using this technology. The mullions are not load bearing but are structurally optimized for self-weight and wind loads. Each mullion was designed and constructed according to its individual structural specifications. For casting, the team utilized steel formworks, and created a formable and compact concrete mixture to minimize friction between the material and the formwork during the casting course. For reinforcement, two twelve-millimeter radius stainless steel rebars were placed inside the formworks prior to casting. In order to avoid deformation in the rebars during the process, they were held in tension and kept fixed by a custom pulley system.

Figure 56: Smart Dynamic Casting technology for production of the mullions in the DFAB House (DFAB House 2020).

A multi-robotic prefabrication set-up made the construction of a geometrically complex timber structure possible. The description on the robotic spatial timber assembly is based on the paper ‘Robotic Fabrication of Bespoke Timber Frame Modules’ by Thoma et al. (Thoma et al. 2019). For the timber structure, all elements were pre-fabricated in ETH Zurich’s Robotic Fabrication Laboratory. The structure needed to meet requirements including the fire code, engineering code, and acoustic transport logistics. The spatial geometry of the frame created the required structural stiffness with no need for reinforcement plates. The beams have generic rectangular profiles and one cut at each end for connection to other components. To simplify the assembly method and meet the structural requirements for shear, tension and compression, the components are connected together by one or two pairs of screws. The cutting angle, milling and drilling vectors for the tension rods and screws are generated by an algorithm and executed by two cooperative industrial robotic arms and a three- axis CNC saw. The robotic arms were attached to a base with three axis of movement which cut, milled, drilled, and assembled the timber beams in a flexible fabrication set up. The robots had the ability to automatically change between tools during the fabrication course without human interference. This system was tested and improved in multiple experiments and finally applied in the construction of the DFAB house.

Figure 57: Multi-robot fabrication of spatial timber structure- DFAB House (ETH Zurich 2018).

Analysis

The DFAB House is a combination of digital in situ fabrication and pre-fabrication. The project is a result of multiple years of research that found application in industry and some of the most cutting-edge technologies are employed to achieve precision in fabrication and push the boundaries of automation in construction sites. Fabrication tools in this project have agency in the course of making and can partially perform fabrication acts independent of human involvement. However, they do not exercise influence over form or design. In this sense, despite the high level of technological advancements, design and making still remain separate.

As the structure is located on top of an already built platform, the project does not face some of the challenges associated with building construction sites. Also, the in-situ fabrication--Mesh Mould—is constructed in a controlled environment similar to a lab or factory. With this understanding, the project does not move far beyond pre-fabrication in a protected lab space.

The project is successful in implementing technology in the course of construction. It is also unique, in that the designers are also the makers. However, the DFAB House maintains a strictly top-down approach in which important design decisions are made early on and are only slightly modified for implementation in construction. This leaves less room for emergence compared to projects with process-oriented methodologies. In the DFAB House, emergence can be seen in limited areas, in relation to traces left on manufactured elements during fabrication with digital tools. Some of the small prototyping for the Smart Slab, helped with determining the design of the components, which could be interpreted as emergence through interaction with digital fabrication tools.

Dubai Municipality Building

Dubai Municipality Building is a two-story 3D printed building by Apis Cor, a US based company specialized in 3D in the construction industry. This is one of the few cases where 3D printing technologies are used for in situ construction of large-scale buildings. As this project is relatively new at the time of writing of this thesis, so there is limited scholarly information about it. The description of this project is from Dezeen (Block 2019), and Business Insider (Mary Meisenzahl 2019).

Figure 58: In-situ robotic 3D printing of Dubai's Municipality Building (Apis Cor 2019).

Description

Dubai Municipality Building by Apis Cor, utilizes an in situ digital fabrication technique. The two-story administrative building was constructed using a 3D printer which was moved around by a crane on the construction site. Apis Cor did multiple mock-ups prior to the construction in order to determine design, construction methods and material specifications. For this project, Apis Cor developed a gypsum-based construction material, which was locally sourced.

Figure 59: Manual labor was necessary in reinforcement of the the 3D printed walls with rebar and more concrete (Apis Cor 2019).

The 3D printing technology significantly reduced the need for human labor on the construction site, and only three workers and the 3D printer were needed for the construction of the building. Despite the cutting-edge technology in the construction of the walls, conventional methods were used in the construction of the foundation of the building. The 3D printed walls were reinforced with traditional construction materials including rebar and concrete. The floor slabs are pre-fabricated and other building components such as windows, doors and wall insulations were also installed manually.

The building is the result of a human-robot collaboration and demonstrate a use of robots in unpredictable conditions of construction sites and in open air. It was only through extensive research and development that a large-scale, complex building was successfully completed.

Analysis

The factor that distinguishes Dubai Municipality Building from other 3D fabricated buildings is the scale and the in-situ digital fabrication technology. This project succeeds in effective implementation of advanced construction technologies in the unpredictable condition of a construction site.

The 3D printer robot in this project is used for efficiency and not for agency. Unlike the fabricators used in the DFAB house, Apis Cor's robot heavily relies on human operators and is a passive tool. However, through effective integration of this passive tool, the project achieve emergence in building form through interaction with passive tools and emergence as happy accidents while making in form of the wall textures.

In this project, design and fabrication happen close to each other. Apis Cor conducted research and multiple mock-up tests to determine structural requirements, which influenced the design of the project. Through interaction with a passive tool and intentional integration of it into the process, design, material, and fabrication technique developed together and influenced each other. This effect is not necessarily seen in the spatial organization of the administrative building, but materiality and construction techniques influenced the design in areas including wall thickness, finish patterns—and therefore the overall geometry of the structure.

<u>Medium-scale Projects</u>

Remote Material Disposition

Remote Material Disposition (RMD) was a loam installation completed by students in a month-long workshop as a proof of concept for an ongoing research on robotic aggregation by Gramazio Kohler Research. RMD introduces a unique process-oriented material-driven fabrication method and explores large-scale architectural applications for robotic aggregation techniques. In concept, the system is simple: a robotic arm is programmed to throw loam material at target points from a distance and erect a structure with potential architectural applications. RMD features a sensing/feedback loop that allows the system to adapt itself throughout the fabrication process. The following is a description about the project's details and specifications from the academic paper "Remote Material disposition" by Doerfler et al (Doerfler et al. 2014).

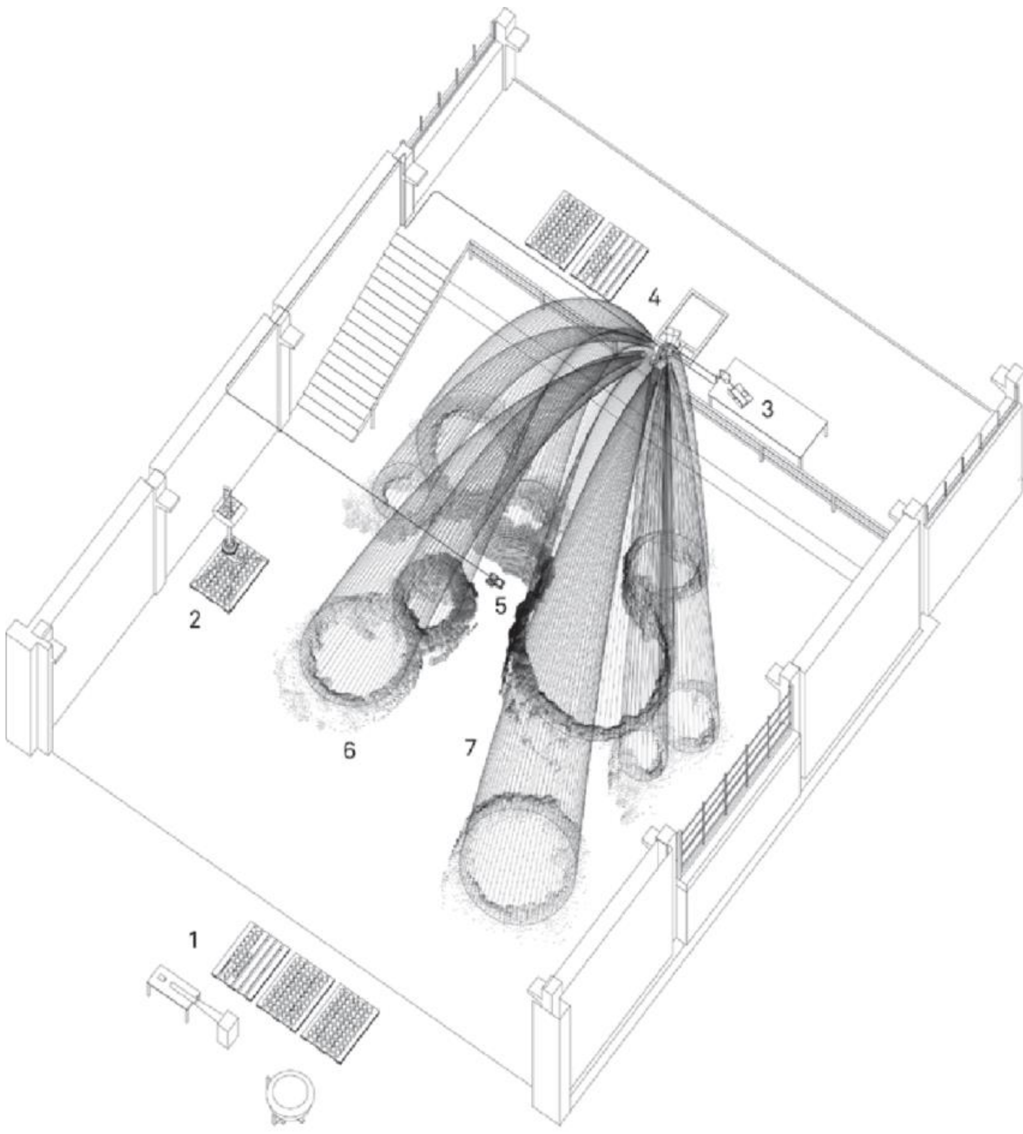

Figure 60: Fabrication setup: "1. Production of loam projectiles, 2. Crane transportation, 3. Laptop for computation and control, 4. Robotic unit with launching actuator for remote material deposition, 5. 3D scanning unit, fixed on the ceiling, 6. 3D scanning point cloud and reference 3D NURBS curves, 7. Simulated trajectories of the loam projectiles aiming at desired targets" (Dörfler 2014).

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Description

In RMD, digital fabrication tools are used not for precision in the making of a pre-determined design, but rather to create a more adaptive and dynamic process with fewer limitations. The project presents a novel method of in situ construction of load bearing non-standard architectural structures where the process of material aggregation replaces precisely defined systems that focus on controlled assembly and definite results. Because many factors related to material behavior could not be modeled or predicted, a sensing system was necessary to provide feedback as the fabrication was in progress. Inspired by an ancient building technique called 'Zabour' from Yemen were loam was manually thrown onto a wall foundation and was gradually constructed in layers, loam was selected for RMD. Loam's sustainability, recyclability, and ability to dissolvable in water were also advantages for the material. Another reason was material behavior as it is similar to other material systems like concrete, wax etc. In this project, loam was mixed, extruded, and cut manually into units.

Figure 61: Robotically fabricated aggregate structure (Roth 2014).

For the installation, a 12 by 12-meter room with a high ceiling of 7 meters was selected. A robotic arm (Universal Robots R5) with a custom launching actuator was installed 2.1 meters above the ground for material deposition. The feedback system included a 3D scanning unit fixed on the ceiling to scan the geometry of the installation including the height, width and material build up areas. The 3D scanner is geometric based, and creates a point cloud-built structure which updates after each loam deposition projectile. The geometrical based feedback system streams this information to the digital domain, which adapts the digital model. This feedback system was necessary to compensate for a multitude of uncertainties including changes in air pressure, friction between the launcher scoop and the material, material deformation at the moment of impact, and structural stability and geometry as the material builds up.

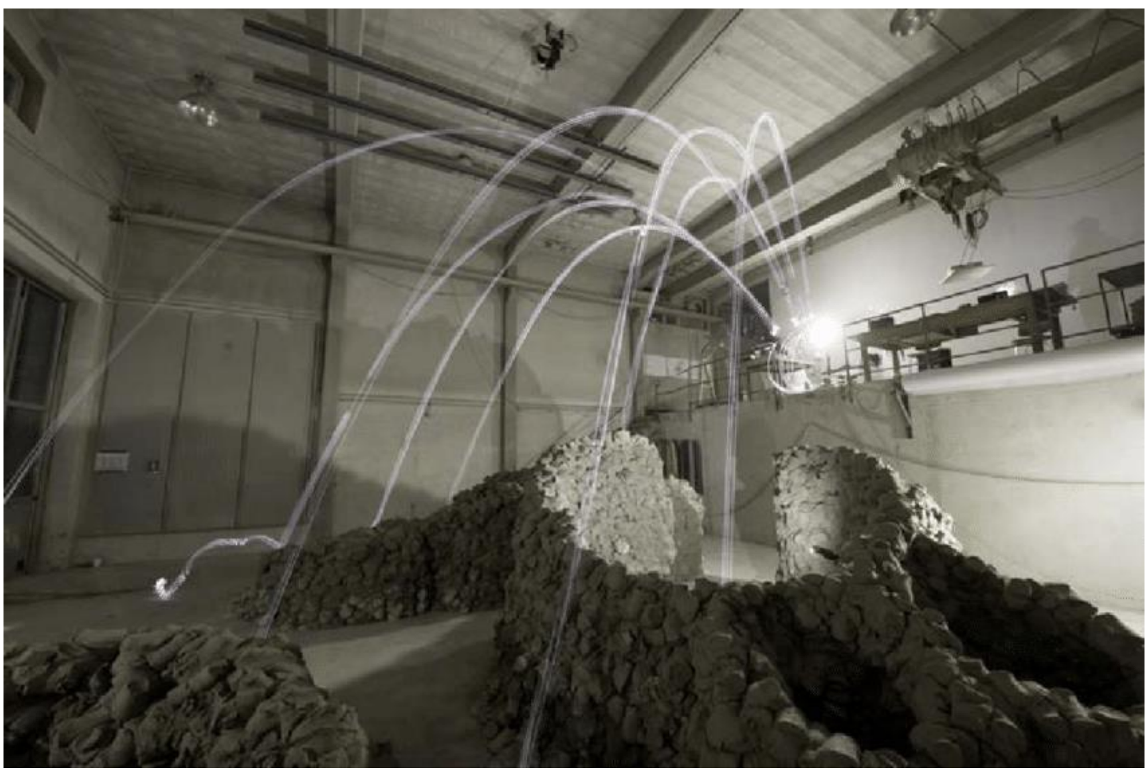

Figure 62: Visualized trajectories of loam projectiles (Lyrenmann 2014).

Analysis

RMD installation shows a successful model of a human-machine collaborative scenario where the human is not the center of the design nor in charge of the whole process and conventional processes and techniques are not relevant. Through this bottom-up collaborative approach, a complex architectural structure was designed and constructed which would not have been easily achieved in a conventional design and making method.

Although, inspired by a traditional construction method, RMD is only possible as a result of technological advancements in architecture. In this project, unlike many other discussed case studies, experimenting with materials and interaction with un-intelligent digital fabrication tools are not enough to achieve the desired results. It is due to the feedback loop that the tools are able to actively participate in the process and provide inputs and determine the final results. However, it should be noted that there are projects that employ similar intelligent/agent tools, but do not achieve the same results. Those projects exploit technological advancements for precision and accuracy in the fabrication of highly detailed and pre-determined designs, and design happens well in advance of construction.

In RMD, as fabrication is in progress the system is in charge of the task and determines the outcomes in a way that removes the system operator from the process. In a process-oriented set-up, RMD achieves emergence through interaction with agent tools and in form of happy accidents during the course of construction.

Silk Pavilion

Silk Pavilion is a medium-scale architectural installation that explores the link between digital and biological fabrication in an architectural context. The research project is completed by the Mediated Mater Group at the MIT Media Lab. The description on this project is primarily based on the research paper ‘Silk Pavilion: A Case Study in Fibre-based Digital Fabrication’ by Oxman et al. (N. Oxman et al. 2017), and ArchDaily (Stott 2013).

Description

The pavilion was inspired by the way silk worms weave cocoons from a single strand of silk. In this research project, Bombyx mori silk worms were studied for their interaction with their environment, their weaving behavior under ambient conditions, and their cocoon weaving patterns. The research involved motion tracking of the silk worms during three-day periods of cocoon construction. During the study, silk worms were placed in enclosed spaces with miniature magnets attached to their heads. Three magnetometers were placed in each box that motion-tracked the worm's movements. The captured data was then converted to a point cloud for visual representation. The teams observed that on a relatively flat surface, the worms tend to generate flat patches of silk, so further studies were done in order to understand the relationship between surface specifications and worms' weaving patterns.

Figure 63: 6,500 silkworms were placed on the base frame to reinforce the gap between robotically woven base (Mediated Matter 2020).

Based on the results from research on silk worms, the team designed and fabricated a primary structure as the pavilion base. The density and position of the apertures was determined algorithmically by material and biological qualities of silk threads and silk worms including silkworms' temperature and light preferences. The design was applied towards CNC weaving of silk threads around a steel frame as the base for the pavilion.

The temporary frame included 26 polygon aluminum panels that were water jet cut individually. A 3 Axis CNC tool was used to weave the primary layer of silk within the panels. Individual panels were manually knotted together edge to edge to form the base frame. After positioning the pavilion in an atrium space, the temporary support was removed and only the woven thread layer was remained. As the final step, 6500 silk worms were placed on the base structure to add reinforcement to the structure by spinning in a period of ten days.

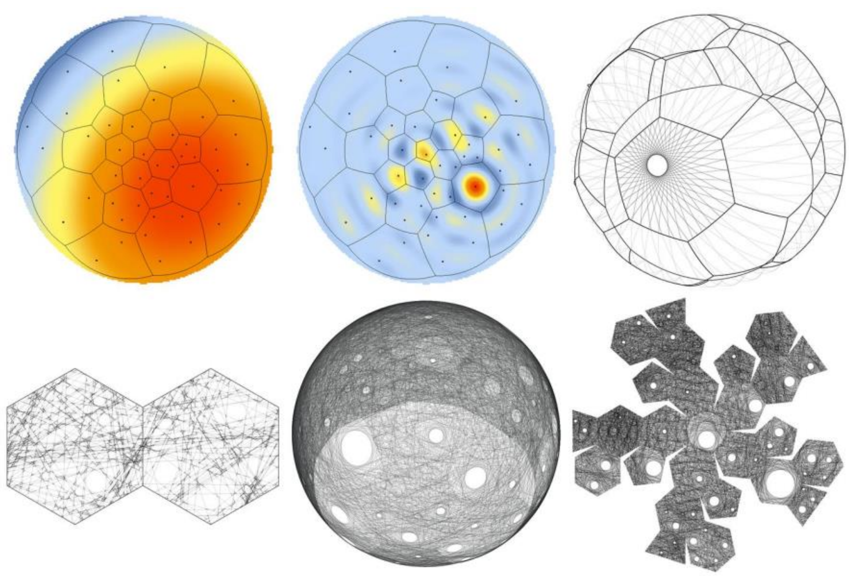

Figure 64: Computational generation of the pavilion's aperture distribution and form. (Mediated Matter 2020)

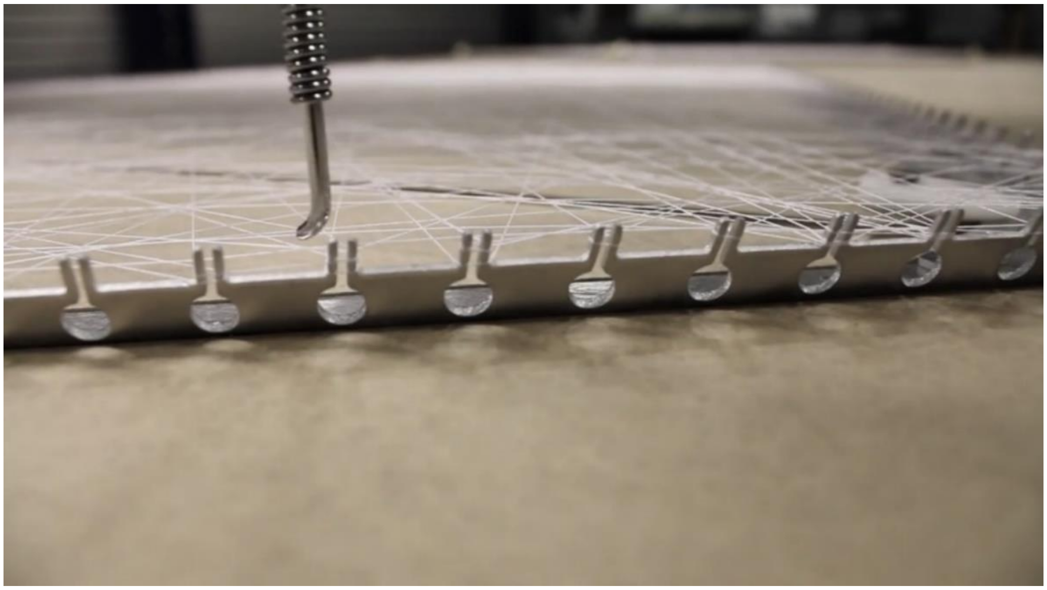

Figure 65: Robotic weaving of the base frame for the Silk Pavilion (Mediated Matter 2020).

Analysis

The Silk Pavilion is unique because of its agenda and methodology. The fabrication techniques used in this project are not the only factors that lead to its success as many of them have been widely used in other contexts. The exceptional aspect of this project is the involvement of non-human actors from concept through implementation.

In most process-oriented and research-based projects, a human still remains in control of the model. This dynamic does not change even when agent digital tools are influential because these tools are curated by their operators. The Silk Pavilion breaks this model. Emergence in form of interaction with agent factors is seen for the Silk Pavilion in which, the designers react to natural factors outside of humans’ influence. This type of interaction has nearly achieved a closed loop where all actors provide direct input on the final outcome. Despite the project’s achievements, this novel approach cannot directly be applied to large-scale projects for the near future.

Conclusions

This thesis examined an extensive range of recent digital design and fabrication projects to identify knowledge gaps and opportunities for research and practice in the architectural digifab domain. It is clear that digital tools provide an opportunity to link the two key aspects of architecture—design and making—and help reduce the divide that emerged between the two as Alberti and others redefined the architect's role during the Renaissance. The adoption of digital tools in architecture has begun, but the impact of this adoption has not been fully realized because digital tools are still being used to facilitate traditional methods and design ideals.

This thesis examines the adoption of digital systems in architecture currently stands and identifies areas for future research. To achieve this goal, the thesis outlined a framework to measure the degree of collaboration in architectural projects where digital fabrication tools are a fundamental part of the collaboration.

The proposed framework has potential application in both profession and academia. For practicing architects who are interested in incorporating digital fabrication tools into their design process, this framework can be used as a guideline to inspire shifts in design approaches by setting project direction and goals to discover new kinds of architecture. This study also allows architects to see how the field stands with its incorporation of new tools and identifies opportunities where architecture can be further developed, such as project delivery methods, streamlined construction models, and complex, novel architectural forms. For academic researchers, the framework can act as a flexible evaluation method for evaluating subjective factors in architectural projects. For researchers working on the development of architectural technology, this framework has the potential to help to identify areas where digital tools should be more impactfully integrated and to develop tools specifically for collaborative design +fabrication scenarios.

Over the past thirty years there has been an increasing trend towards integration of digital fabrication tools and collaborative systems into architecture. This increase is visible at both large and medium-scale architectural projects – where large-scale project generally include entire buildings or parts of buildings., Medium-scale projects—mostly applied research projects—have become quite common as a means to demonstrate the application of new digitally-driven design-to-fabrication processes. These demonstration projects and those that will follow have to the potential to enable a shift towards an architecture resultant from and informed by the availability of digital tools in architectural practice.

The thesis concludes that in projects with higher degree of human to digital-system collaboration, emergent design is more prevalent. For example, in a project like the RMD (Doerfler et al. 2014), the installation was realized as the results of a structured interactive process that took input from both the tools/robot and humans. Therefore, this process resulted in one of the few studied examples of a true emergent outcome. In the current state of the field, even in projects where cutting-edge methods and machines are used, there is a tendency to deploy technology for precision and accuracy instead of seeking emergence in design. Advanced tools with agency are used for automation of construction rather than having input in the design process. These findings suggest two different trends. First, shifts in the use of architectural technology are occurring but are overstated. Second, there is resistance to major technological shifts in favor of conventional design-making models where the designer remains in control of the entire architectural process. This thesis showed that shifts towards the re-integration of design and production are possible, regardless of the level of technological advancement, as the generation of new design-making paradigms is primarily a matter of attitude and intent, not the power or advanced intelligence of the technology used.

The author believes that the new digital design-making approaches are on the horizon and it is only through the intentional and conscious structuring of design-making models that architecture will move forward. Progress in three areas is necessary for the incorporation of digital systems into architecture: 1) activation of making in the design process, 2) utilizing tools and machines true to their inherent qualities, and 3) switching focus from goal-oriented to process-oriented and interactive methods.

In an ideal process, making is present in all design phases and design takes form as we make. When making is incorporated into the design process, the designer faces challenges that they will inevitably face later in the process while there is still opportunity and space to address them. If making is activated in design, roles within the field will transform as architects become involved in post-design phases that they currently are distanced from.

Because fabrication/construction tools are fundamental to making, architects should become familiar with the purpose tools are built for and design their process around it. Alternatively, architects should learn to tailor tools specifically for their needs. At present, architects bring in non-native digital fabrication tools and force the tools and their own process to the fixed architectural framework, which leads to wasted effort and limitations on both sides. Utilizing tools per their inherent qualities will result in modification of the roles and dynamics within the field of architecture and a decrease in redundancies as machines/tools are used where and how they are best fit.

The previous two conditions lay foundation for successful process-oriented design models. The shift from goal-oriented to process-oriented requires the designer to give up some control and trust their tools. A new advantage of giving up control comes from the opportunity of agent tools, which can add new forms of intelligence to the design process. The focus and energy that often is applied towards precision in achieving goals must shift toward development of processes that allow for exploration and discovery.

Future Work

One limitation in this thesis was the project selection. As there is not a single comprehensive source to discover projects, the case studies in this research were well known projects discovered through architecture publications, this selection might not be a representative of the full range of work done in the field. In future work, the project selection should be diversified to capture a more representative range of digital fabrication projects. One way to broaden the projects' list is to work with research labs and/or universities to include the most cutting edge ongoing and upcoming projects.

A second limitation was that the discussed design-making methods in the literature review were limited to scholarly discussions within the field of architecture. Other new design to making approaches could be discovered by reviewing work outside of the field of architecture including traditional crafts and art, manufacturing and engineering.

Future work will challenge and validate the approach and conclusions of this thesis by expanding it to a larger sample size and by having other researchers/designers evaluate these projects to see if similar conclusions are reached. In addition, it is suggested that the framework be applied to real-life projects to observe if awareness of new methods can inspire change in the architectural process and triggers emergent results.

The utility of this approach is likely dependent on project scope and scale, so it should be tested in small-scale, medium-scale, and large-scale projects in both research and design practice, so that the results can be compared. In order to apply this framework to small-scale projects, this study should be expanded to include projects at that scale. The analysis was helpful in understanding general past and current trends, but might not be sufficient for projecting future developments. Smaller scale projects taking place in research labs will be implemented in medium and large-scale projects in the future. For future works, it is essential to study the on-going research on the fundamental technologies that will address the architecture of tomorrow.

Technology has brought the designer closer in contact to materials and the realities of construction. If technology is combined with a shift in attention towards collaboration and interactivity, architecture can reach for brand-new opportunities and possibilities.

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